



**INDOOR ENVIRONMENT  
DEPARTMENT  
PUBLICATIONS  
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**Publications by the Indoor Environment Department  
Berkeley, CA 94720**

### **2002 Publications with Abstracts**

**Abadie, Marc O., Elizabeth U. Finlayson and Ashok J. Gadgil. "Infiltration heat recovery in building walls: Computational fluid dynamics investigations results". 2002. LBNL-51324.**

#### **ABSTRACT**

Conventional calculations of heating (and cooling) loads for buildings assume that conduction heat loss (or gain) through walls is independent of air infiltration heat loss (or gain). During passage through the building envelope, infiltrating air substantially exchanges heat wall insulation leading to partial recovery of heat conducted through the wall. The Infiltration Heat Recovery (IHR) factor was introduced to quantify the heat recovery and correct the conventional calculations.

In this study, Computational Fluid Dynamics was used to calculate infiltration heat recovery under a range of idealized conditions, specifically to understand factors that influence it, and assess its significance in building heat load calculations. This study shows for the first time the important effect of the external boundary layers on conduction and infiltration heat loads.

Results show (under the idealized conditions studied here) that (1) the interior details of the wall encountered in the leakage path (i.e., insulated or empty walls) do not greatly influence the IHR, the overall relative location of the cracks (i.e., inlet and outlet locations on the wall) has the largest influence on the IHR magnitude, (2) external boundary layers on the walls substantially contribute to IHR and (3) the relative error in heat load calculations resulting from the use of the conventional calculational method (i.e., ignoring IHR) is between 3% and 13% for infiltrating flows typically found in residential buildings.

**Abushakra, Bass, Iain S. Walker and Max H. Sherman. "A study of pressure losses in residential air distribution systems". *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings*; Pacific Grove, California; August 18-23, 2002, Vol. 1, pp.1-14, American Council for an Energy Efficient Economy, Washington, DC. LBNL-49700.**

#### **ABSTRACT**

An experimental study was conducted to evaluate the pressure drop characteristics of residential duct system components that are either not available or not thoroughly (sometimes incorrectly) described in existing duct design literature. The tests were designed to imitate cases normally found in typical residential and light commercial installations. The study included three different sizes of flexible ducts, under different compression configurations, splitter boxes, supply boots, and a fresh air intake hood. The experimental tests conformed to ASHRAE Standard 120P – *Methods of Testing to Determine Flow Resistance of HVAC Air Ducts and Fittings*. The flexible duct study covered compressibility and bending effects on the total pressure drop, and the results showed that the available published references tend to underestimate the effects of compression in flexible ducts that can increase pressure drops by up to a factor of nine. The supply boots were tested under different configurations including a setup where a flexible duct elbow connection was considered as an integral part of the supply boot. The supply boots results showed that diffusers can increase the pressure drop by up to a factor of two in exit fittings, and the installation configuration can increase the pressure drop by up to a factor of five. The results showed that it is crucial for designers and contractors to be aware of the compressibility effects of the flexible duct, and the installation of supply boots and diffusers.

**Abushakra, Bass. Longevity of duct tape in residential air distribution systems: 1-D, 2-D, and 3-D joints. LBNL-51099. No Abstract available.**

**Apte, M., Hodgson, A., Shendell, D., Dibartolomeo, D., Hotchi, T., Kumar, S., Lee, Seung-Min, Liff, S., Rainer, L., Schmidt, R., Sullivan, D., Diamond, R., Fisk, W.J., (2002) "Energy and indoor environmental quality in relocatable classrooms". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 2, pp.62-69, Indoor Air 2002, Santa Cruz, CA. LBNL-49581.**

## ABSTRACT

Relocatable classrooms (RCs) are commonly utilized by school districts with changing demographics and enrollment sizes. Four energy-efficient RCs were designed and constructed for this study to demonstrate technologies that simultaneously attempt to improve energy efficiency and indoor environmental quality (IEQ). Two were installed at each of two school districts, and energy use and IEQ parameters were monitored during occupancy. Two (one per school) were finished with materials selected for reduced emissions of toxic and odorous volatile organic compounds (VOCs). Each RC had two HVAC systems, alternated weekly, consisting of a standard heat-pump system and an indirect-direct evaporative cooling (IDEC) system with gas-fired hydronic heating. The hypothesized advantages of the IDEC include continuous outside air ventilation at  $\geq 7.5 \text{ L s}^{-1}$  per person,  $\sim 70\%$  less cooling energy and efficient particle filtration. Measurements include: carbon dioxide, particles, VOCs, temperature, humidity, thermal comfort, noise, meteorology, and energy use. Preliminary IEQ monitoring results are reported.

**Apte, Michael, Lara Gundel, Raymond Dod, Gee-Min Chang, and Richard Sextro. "A pilot study of the behavior of gas- and particle-phase ETS tracers in residences". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 2, pp. 500-505, Indoor Air 2002, Santa Cruz, CA. LBNL-49585.**

## ABSTRACT

Our previous study of environmental tobacco smoke (ETS) in a three-room environmental chamber showed that smoking history significantly influenced inter-room ETS transport, particularly of gas-phase nicotine. We conducted a three-home pilot study where smoking was limited to one room. Single-smoker residences were monitored during five one-week periods while the smoker participated in a smoking cessation program. Nicotine traced ETS particles were detected reliably in the smoking rooms (SRs) and unreliably in the non-smoking rooms (NSRs). On average, the ventilation- and volume-normalized smoking rate,  $0.1 \text{ Cigarette} \cdot \text{h}^{-1} \cdot \text{m}^{-3}$ , added about 17 and  $4 \mu\text{g m}^{-3}$  of ETS particles into the SR and NSR, while average nicotine concentration increases were 2 and  $0.06 \mu\text{g m}^{-3}$ , respectively. Thus, nicotine tracers may underestimate ETS particle exposure in a NSR (e.g., a child's bedroom) by a factor of 2 to 8. In other words, ETS exposure predicted from nicotine concentrations could be almost an order of magnitude lower than actual exposure.

**Bennett, Deborah H., Thomas E. McKone, John.S. Evans, William W. Nazaroff, Manuele D. Margni, Olivier Jolliet, and Kirk R. Smith. "Defining intake fraction". *Environmental Science & Technology* v.36; pp.207A-211A; May 1, 2002. LBNL-50501.**

## ABSTRACT

Activities such as comparative risk analysis, life-cycle assessment, emissions trading and sustainable development are creating a growing demand for reliable and consistent information about the potential adverse effects of the thousands of chemicals released to the environment. This demand has fostered measurement and modeling efforts that link emissions to the resulting human exposures and subsequent health effects for a wide range of human products and activities, such manufacture and disposal of consumer goods, cooking, smoking, energy conversion, industrial production, and agriculture. For many pollutants, a preliminary estimate of the human health risk that is posed by an environmental release can be determined from the combination of three factors: (1) the quantity released; (2) the incremental intake per unit release; and (3) the risk of adverse effect per unit intake. This paper addresses the second term, the emissions-to-intake relationship. As discussed in a recent literature review, several researchers have independently developed similar approaches for relating source emissions to human intake for various pollutants and exposure pathways. Consequently, multiple terms, definitions, and units exist for what appears to be a single, yet multifaceted concept. But there are inconsistencies both in terminology and definitions among various researchers quantifying emissions-to-intake relationships. Differences in definitions leads to unnecessary complexity in comparing results from different research groups. Inconsistency in terminology when the same quantity is being calculated leads to further lack of transparency. We formed a working group and prepared this article to communicate our recommendations for a set of terms and associated definitions that are descriptive, simple, accurate, and consistent both with common usage and usage in all relevant disciplines; are flexible to permit application over a broad range of potential uses; and reflect consensus among a large number of researchers. We propose the term *intake fraction* (*iF*) as the primary label for quantifying the emissions-to-intake relationship.

Because the effort to employ intake fraction is in its early stages and is gaining momentum, now is the time to build consensus on terminology. Doing so will allow us to communicate more effectively both among ourselves and also with practitioners in related fields.

**Bennett, D.H., M.D. Margni, T.E. McKone, and O. Jolliet, "Intake Fraction for Multimedia Pollutants: A Tool for Life Cycle Analysis and Comparative Risk Assessment," *Risk Analysis* v.22; no.5; pp. 903-916; October 2002, LBNL-47253**

#### **ABSTRACT**

We employ the concept of Intake Fraction ( $iF$ ) as an effective way to understand the source-to-dose relationship for pollutant emissions in Life Cycle Analysis (LCA) or comparative risk assessment. Intake fraction is the fraction of chemical mass emitted into the environment that eventually passes into a member of the population through inhalation, ingestion, or dermal exposure. To date, this concept has been primarily applied to pollutants whose primary route of exposure is inhalation. Here we extend the use of  $iF$  to multimedia pollutants with multiple exposure pathways. We use a level III multimedia model to calculate  $iF$  for TCDD and compare the results to one calculated from measured levels of dioxin toxic equivalents in the environment. We calculate  $iF$  for emissions to air and surface water for 244 chemicals. We correlate the primary exposure route with the magnitudes of the octanol-water partition coefficient,  $K_{ow}$ , and of the air-water partitioning coefficient (dimensionless Henry constant),  $K_{aw}$ . This results in value ranges of  $K_{ow}$  and  $K_{aw}$  where the chemical exposure route can be classified with limited input data requirements as primarily inhalation, primarily ingestion, or multi-pathway. For the inhalation and ingestion dominant pollutants, we also define empirical relationships based on chemical properties for quantifying dose fraction. The empirical relationships facilitate rapid evaluation of many chemicals in terms of the potential dose. By defining a theoretical upper limit for  $iF$  in a multimedia environment we find that  $iF$  calculations provide insight into the multimedia model algorithms and help identify unusual patterns of exposure and questionable exposure model results.

**Bennett DH, Furtaw EJ, McKone TE (2002): A fugacity-based indoor residential pesticide fate model. *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 1, pp. 261-266, Indoor Air 2002, Santa Cruz, CA.**

#### **ABSTRACT**

Dermal and non-dietary pathways are potentially significant exposure pathways to pesticides used in residences. Exposure pathways include dermal contact with residues on surfaces, ingestion from hand- and object-to-mouth activities, and absorption of pesticides into food. A limited amount of data has been collected on pesticide concentrations in various residential compartments following an application. But models are needed to interpret this data and make predictions about other pesticides based on chemical properties. In this paper, we propose a mass-balance compartment model based on fugacity principles. We include air (both gas phase and aerosols), carpet, smooth flooring, and walls as model compartments. Pesticide concentrations on furniture and toys, and in food, are being added to the model as data becomes available. We determine the compartmental fugacity capacity and mass transfer-rate coefficient for wallboard as an example. We also present the framework and equations needed for a dynamic mass-balance model.

**Bodnar, A.B., R.L. Maddalena and T.E. McKone. "Addressing locally grown foods in cumulative exposure assessments". Submitted to *Journal of Exposure Analysis and Environmental Epidemiology*, (July, 2002). LBNL-50378.**

#### **ABSTRACT**

Both laboratory and field studies confirm the importance of vegetation for scavenging semi-volatile organic chemicals (SVOCs) from the atmosphere and a number of exposure studies have found that the dietary pathway is often a significant contributor to cumulative exposure for these chemicals. Exposure calculations based on published concentration data for foods indicate that the potential intake through ingestion is up to 1000 times that of inhalation for several persistent SVOCs. However, little information exists on the source-to-dietary intake linkage for SVOC's. Because of higher SVOC emissions to urban regions, this linkage is particularly important for foods that are grown, distributed and consumed in or near urban regions. The food pathway can also contribute to dietary exposure for populations that are remote from a pollutant source if the pollutants can migrate to agricultural regions and subsequently to the agricultural commodities distributed to that population. We use the characteristic travel distance (CTD) and available data within the CalTOX multimedia model framework to assess the contribution of local food markets to the fraction of cumulative food intake that is attributable to local sources. For a set of three representative multimedia SVOCs- benzo(a)pyrene, fluoranthene, and 2,3,7,8-TCDD, we explore the contribution of airborne SVOC's to cumulative uptake through the local food consumption pathway. We use the population based intake fraction ( $iF$ ) to determine how SVOC intake varies among food commodities and compares to inhalation. The approach presented here provides a useful framework and starting point for source-to-intake assessments for the air-to-dietary exposure pathway.

**Carrié, F. R., Levinson, R., Xu, T. T., Dickerhoff, D. J., Fisk, W. J., McWilliams, J., Modera, M. P., Wang, D. 1999. "Laboratory and field testing of an aerosol-based duct-sealing technology for large commercial buildings". Published in *ASHRAE Transactions*, Jan. 2002. LBNL-44220.**

#### **ABSTRACT**

Laboratory and field experiments were performed to evaluate the feasibility of sealing leaks in commercial duct systems with an aerosol sealant. The method involves blowing an aerosol through the duct system to seal the leaks from the inside, the principle being that the aerosol particles deposit in the cracks as they try to escape under pressure. It was shown that the seals created with the current sealant material can withstand pressures far in excess of what is found in commercial-building duct systems. We also performed two field experiments in two large-commercial buildings. The ASHRAE leakage classes of the systems were reduced from 653 down to 103, and from 40 down to 3. Methods and devices specifically devised for this application proved to be very efficient at (a) increasing the sealing rate and (b) attaining state-of-the-art duct leakage classes. Additional research is needed to improve the aerosol injection and delivery processes.

**Castorina, R., A. Bradman and T.E. McKone. "Assessing cumulative organophosphate pesticide exposure and risk among pregnant women living in an agricultural community". Submitted to *Environmental Health Perspectives* (August, 2002) LBNL-51334.**

#### **ABSTRACT**

Approximately 225,000 kilograms of organophosphate (OP) pesticides are used annually in California's Salinas Valley, which is intensively farmed for vegetables and fruit. These activities have raised concerns about pesticide exposures to area residents. As part of a prospective cohort study, we collected three spot urine samples from 462 pregnant women and analyzed them for six dialkyl phosphate metabolites. Based on these urinary metabolite concentrations, we estimated OP pesticide doses with deterministic steady-state models using two methods: the first method assumed the pesticide metabolites were attributable entirely to a single diethyl or dimethyl OP pesticide; the second method adapted U.S. EPA draft guidelines for cumulative risk assessment to estimate dose from a mixture of OP pesticides that share a common mechanism of toxicity. We used pesticide use reporting data for the Salinas Valley to quantify the likely mixture to which the women were exposed. Based on average OP pesticide dose estimates that assumed exposure to a single OP pesticide (Method 1), between 0% and 36.0% of study participants' exposures exceeded the U.S. EPA oral benchmark dose<sub>10</sub> (BMD<sub>10</sub>) divided by a 100-fold uncertainty factor, depending on the assumption made about the parent compound. These BMD<sub>10</sub> values were derived from studies of brain cholinesterase inhibition in rats. 14.7% of the participants' average cumulative OP pesticide dose estimates (Method 2) exceeded the BMD<sub>10</sub> of the selected index chemical divided by a 100-fold uncertainty factor, regardless of index chemical chosen. An uncertainty analysis of the pesticide mixture parameter suggests that this point estimate could range from 1%-38%. Because our reference value (BMD<sub>10</sub>/100) may not account for the special sensitivity of the developing fetus, this research points to the need for modeling approaches to estimate fetal exposures and assess risk from prenatal OP pesticide exposure.

**Cox, S.S., Little, J.C., Hodgson, A.T. (2002) "Predicting the emission rate of volatile organic compounds from vinyl flooring", *Environmental Science & Technology* 36:709-714. LBNL-47094.**

#### **ABSTRACT**

A model for predicting the rate at which a volatile organic compound (VOC) is emitted from a diffusion-controlled material is validated for three contaminants (n-pentadecane, n-tetradecane, and phenol) found in vinyl flooring (VF). Model parameters are the initial VOC concentration in the material-phase ( $C_0$ ), the material/air partition coefficient (K), and the material-phase diffusion coefficient (D). The model was verified by comparing predicted gas-phase concentrations to data obtained during small-scale chamber tests, and by comparing predicted material-phase concentrations to those measured at the conclusion of the chamber tests. Chamber tests were conducted with the VF placed top side up and bottom side up. With the exception of phenol, and within the limits of experimental precision, the mass of VOCs recovered in the gas phase balances the mass emitted from the material phase. The model parameters ( $C_0$ , K, and D) were measured using procedures that were completely independent of the chamber test. Gas- and material-phase predictions compare well to the bottom-side-up chamber data. The lower emission rates for the top-side-up orientation may be explained by the presence of a low-permeability surface layer. The sink effect of the stainless steel chamber surface was shown to be negligible.

**Craig, Paul, Ashok Gadgil and Jonathan Koomey. "What can history teach us?: A retrospective analysis of long-term energy forecasts for the U.S.". LBNL-50498. No Abstract available.**

**Daisey, J.M., W.J. Angell, and M.G. Apte. 2002. "Indoor Air Quality, Ventilation and Health Symptoms in Schools: An Analysis of Existing Information," *Indoor Air*, in press. LBNL-48287.**

**ABSTRACT**

We reviewed the literature on indoor air quality (IAQ), ventilation, and building-related health problems in schools and identified commonly reported building-related health symptoms involving schools until 1999. We collected existing data on ventilation rates, carbon dioxide (CO<sub>2</sub>) concentrations and symptom-relevant indoor air contaminants, and evaluated information on causal relationships between pollutant exposures and health symptoms. Reported ventilation and CO<sub>2</sub> data strongly indicate that ventilation is inadequate in many classrooms, possibly leading to health symptoms. Adequate ventilation should be a major focus of design or remediation efforts. Total volatile organic compounds, formaldehyde and microbiological contaminants are reported. Low formaldehyde concentrations were unlikely to cause acute irritant symptoms (<0.05 ppm), but possibly increased risks for allergen sensitivities, chronic irritation, and cancer. Reported microbiological contaminants included allergens in deposited dust, fungi and bacteria. Levels of specific allergens were sufficient to cause symptoms in allergic occupants. Measurements of airborne bacteria and airborne and surface fungal spores were reported in schoolrooms. Asthma and "sick building syndrome" symptoms are commonly reported. The few studies investigating causal relationships between health symptoms and exposures to specific pollutants suggest that such symptoms in schools are related to exposures to volatile organic compounds (VOCs), molds and microbial VOCs, and allergens.

**De Martinis, B.S.; R.A. Okamoto, N.Y. Kado, L.A. Gundel and L.R.F. Carvalho, Polycyclic aromatic hydrocarbons in a bioassay-directed fractionated extract of PM10 collected in Sao Paulo, Brazil, *Atmos. Environ.* 36, 307-314 (2002), LBNL-48453. No Abstract available.**

**Diamond, Rick. *What might U.S. homes and workplaces be like in the year 2020--and what are the implications for energy use?* (2002) LBNL-50184.**

**ABSTRACT**

Can lifestyle-based scenarios provide insight into the nature of energy use in our future buildings? Participants in a design charrette brainstormed ideas about the future of US homes and workplaces. The teams started from several descriptions of daily lifestyles, and developed specific building characteristics as the place settings for these narratives. In addition to the characterization of the physical environment, we also speculate as to the forces that would be influential in making these changes. Further reflection was made on the possible unintended consequences of these changes. The rationale for this exercise was to broaden the discussion on future energy use by looking at future scenarios in the context of everyday life.

**Diamond, Rick. "A lifestyle-based scenario for U.S. buildings: Implications for energy use". LBNL-50969. Accepted for publication in *Energy Policy*, March 2002.**

**ABSTRACT**

Can lifestyle-based scenarios provide insight into the nature of energy use in our future buildings? Participants in a design charrette brainstormed ideas about the future of US homes and workplaces. The teams started from several descriptions of daily lifestyles, and developed specific building characteristics as the place settings for these narratives. In addition to characterizing the physical environment, the teams also identified the forces that would be influential in making these changes. Further reflection was made on the possible unintended consequences of these changes. The energy implications of these changes were characterized with respect to magnitude and direction. While acknowledging the speculative nature of the exercise, the rationale was to broaden the discussion on future energy use by looking at future scenarios in the context of everyday life.

**Diamond, R.C. and M. Moezzi. "Becoming allies: Combining social science and technological perspectives to improve energy research and policy making". *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, California; August 18-23, 2002, Vol. 4, pp. 89-104, American Council for an Energy Efficient Economy, Washington, DC LBNL-50704.**

**ABSTRACT**

Within the energy research community, social sciences tends to be viewed fairly narrowly, often as simply a marketing tool to change the behavior of consumers and decision makers, and to “attack market barriers.” As we see it, social sciences, which draws on sociology, psychology, political science, business administration, and other academic disciplines, is capable of far more. A social science perspective can re-align questions in ways that can lead to the development of technologies and technology policy that are much stronger and potentially more successful than they would be otherwise. In most energy policies governing commercial buildings, the prevailing R&D directives are firmly rooted in a technology framework, one that is generally more quantitative and evaluative than that fostered by the social sciences. To illustrate how social science thinking would approach the goal of achieving high energy performance in the commercial building sector, we focus on the U.S. Department of Energy’s Roadmap for commercial buildings (DOE 2000) as a starting point. By “deconstructing” the four strategies provided by the Roadmap, we set the stage for proposing a closer partnership between advocates of technology-based and social science-based approaches.

**Erdmann, C.A., Steiner, K.C., Apte, M.G., (2002) “Indoor carbon dioxide concentrations and SBS symptoms in office buildings revisited: Analyses of the 100 building BASE Study dataset”. *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 3, pp. 443-448. Indoor Air 2002, Santa Cruz, CA. LBNL-49584.**

#### **ABSTRACT**

In previously published analyses of the 41-building 1994-1996 USEPA Building Assessment Survey and Evaluation (BASE) dataset, higher workday time-averaged indoor minus outdoor CO<sub>2</sub> concentrations (dCO<sub>2</sub>) were associated with increased prevalence of certain mucous membrane and lower respiratory sick building syndrome (SBS) symptoms, even at peak dCO<sub>2</sub> concentrations below 1,000 ppm. For this paper, similar analyses were performed using the larger 100-building 1994-1998 BASE dataset. Multivariate logistic regression analyses quantified the associations between dCO<sub>2</sub> and the SBS symptoms, adjusting for age, sex, smoking status, presence of carpet in workspace, thermal exposure, relative humidity, and a marker for entrained automobile exhaust. Adjusted dCO<sub>2</sub> prevalence odds ratios for sore throat and wheeze were 1.17 and 1.20 per 100-ppm increase in dCO<sub>2</sub> (p <0.05), respectively. These new analyses generally support our prior findings. Regional differences in climate, building design, and operation may account for some of the differences observed in analyses of the two datasets.

**Faulkner, D., Fisk, W.J., Sullivan, D.P., Lee, S.M., (2002) “Ventilation efficiencies of a desk-edge-mounted task ventilation system”. *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 4, pp.1060-65. Indoor Air 2002, Santa Cruz, CA. LBNL-49939.**

#### **ABSTRACT**

In chamber experiments, we investigated the effectiveness of a task ventilation system with an air supply nozzle located underneath the front edge of a desk and directing air toward a heated mannequin seated at the desk. The task ventilation system provided outside air, while another ventilation system provided additional space cooling but no outside air. Test variables included the vertical angle of air supply (-15° to 45° from horizontal), and the supply flow rate of (3.5 to 6.5 L s<sup>-1</sup>). Using the tracer gas step-up and step-down procedures, the measured air change effectiveness (i.e., exhaust air age divided by age of air at the mannequin’s face) ranged from 1.4 to 2.7, which is higher than typically reported for commercially available task ventilation or displacement ventilation systems.

**Federspiel, C.C., Liu, G., Lahiff, M., Faulkner, D., Dibartolomeo, D.L., Fisk, W.J., Price, P.N., Sullivan, D.P. “Worker performance and ventilation: Analyses of individual data for call-center workers”. *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 1, pp.796-801. Indoor Air 2002, Santa Cruz, CA. LBNL-50124.**

#### **ABSTRACT**

We investigated the relationship between ventilation rates and work performance in a call center. We randomized the ventilation controls and measured ventilation rate, differential carbon dioxide (ΔCO<sub>2</sub>) concentration, temperature, humidity, occupant density, degree of under-staffing, shift length, time of day, and time required to complete two different work performance tasks (talk and wrap-up). ΔCO<sub>2</sub> concentrations ranged from 13 to 611 ppm. We used multi-variable regression to model the association between the predictors and the responses. We found that agents performed talk tasks fastest when the ventilation rate was highest, but that the relationship between talk performance and ventilation was not monotone. We did not find a statistically significant association between wrap-up performance and ventilation. At high temperatures agents were slower at both the talk and wrap-up tasks. Agents were slower at wrap-up during long shifts and when the call center was under-staffed.

**Federspiel, C., H. Li, D. Auslander, D. Lorenzetti, and A. Gadgil. "Modeling transient contaminant transport in HVAC systems and buildings", *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 4, pp.217-222. Indoor Air 2002, Santa Cruz, CA. LBNL-49603.**

**ABSTRACT**

A mathematical model of the contaminant transport in HVAC systems and buildings is described. The model accounts for transients introduced by control elements such as fans and control dampers. The contaminant transport equations are coupled to momentum equations and mass continuity equations of the air. To avoid modeling variable transport delays directly, ducts are divided into a large number of small sections. Perfect mixing is assumed in each section. Contaminant transport equations are integrated with momentum equations in a way that guarantees mass continuity by using two non-negative velocities for computing the mass transport between elements. Computer simulations illustrate how the model may be used to analyze and design control systems that respond to a sudden release of a toxic contaminant near a building. By coupling transient flow prediction with transient contaminant prediction, the model overcomes a number of problems with existing contaminant transport codes.

**Finlayson, E.U., A.J. Gadgil and T.L. Thatcher. "Pollutant dispersion in a large indoor space: Computational Fluid Dynamics (CFD) predictions and comparison with a scale model experiment for isothermal flow". LBNL-50105.**

**ABSTRACT**

A mathematical model of the contaminant transport in HVAC systems and buildings is described. The model accounts for transients introduced by control elements such as fans and control dampers. The contaminant transport equations are coupled to momentum equations and mass continuity equations of the air. To avoid modeling variable transport delays directly, ducts are divided into a large number of small sections. Perfect mixing is assumed in each section. Contaminant transport equations are integrated with momentum equations in a way that guarantees mass continuity by using two non-negative velocities for computing the mass transport between elements. Computer simulations illustrate how the model may be used to analyze and design control systems that respond to a sudden release of a toxic contaminant near a building. By coupling transient flow prediction with transient contaminant prediction, the model overcomes a number of problems with existing contaminant transport codes.

**Fischer, M., Littlejohn D., M. Lunden, L. Gundel, R. Dod, and N. Brown. "An instrument for automated simultaneous measurements of ammonia and nitric acid in indoor and outdoor air". LBNL-51005. No Abstract available.**

**Fischer, Marc L., Melissa M. Lunden, Tracy L. Thatcher, David Littlejohn, Thomas W. Kirchstetter, Susanne V. Hering, Richard G. Sextro, and Nancy J. Brown. "Building a predictive model of indoor concentrations of outdoor PM-2.5 for a residential research house in Clovis, California". LBNL-51001.**

**ABSTRACT**

The prevalence of relocatable classrooms (RCs) at schools is rising due to federal and state initiatives to reduce K-3 class size, and limited capital resources. Concerns regarding inadequate ventilation and indoor air and environmental quality (IEQ) in RCs have been raised. Adequate ventilation is an important link between improved IEQ and energy efficiency for schools. Since students and teachers spend the majority of a 7-8 hour school day inside classrooms, indoor contaminant concentrations are assumed to drive personal school-day exposures. We conducted a demonstration project in new relocatable classrooms (RCs) during the 2001-02 school year to address these issues. Four new 24' x 40' (960 ft<sup>2</sup>) RCs were constructed and sited in pairs at an elementary school campus in each of two participant school districts (SD) in Northern California. Each RC was equipped with two heating, ventilation, and air conditioning (HVAC) systems, one per module. The two HVAC systems were a standard heat pump with intermittent 25-50% outdoor air ventilation and an energy-efficient advanced system, based on indirect-direct evaporative cooling with an integrated natural gas-fired hydronic heating loop and improved particle filtration, providing continuous 100% outdoor air ventilation at  $\geq 15 \text{ ft}^3 \text{ min}^{-1} \text{ occupant}^{-1}$ . Alternate carpets, wall panels, and ceiling panels were installed in two classrooms – one in each pair – based on the results of a laboratory study of VOC emissions from standard and alternate materials. Numerous IEQ and outdoor air quality and meteorological parameters were measured either continuously over the school year or as integrated school day samples during the fall cooling and winter heating seasons. Details of the RC designs, the field monitoring methodology including handling, storage, transport and management of chemical samples and data, and analyses to be conducted are presented.



Fischer, M.L., Lunden, M.M., Thatcher, T.L., Sextro, R.G., Brown, N.J. (2002) "Predicting Indoor PM<sub>2.5</sub> Of Outdoor Origin: Testing a transient size-resolved Model Using Intensive Measurements From A Residence". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 1, pp.152-157. Indoor Air 2002, Santa Cruz, CA.. LBNL-49615.

#### ABSTRACT

We report tests of a model for indoor PM<sub>2.5</sub> of outdoor origin that incorporates physical mechanisms for time dependent transport, and size dependent penetration and deposition. This work was performed using information obtained from an intensive study of a house near Fresno, CA, USA. During the multi-week study covering two seasons, we measured particles in both indoor and outdoor air, with high temporal, chemical, and size resolution, and other variables that also affect transport and fate. Results suggest that 1) the model captures a significant fraction of the variation in meteorologically forced air infiltration rate, 2) the predicted indoor/outdoor PM<sub>2.5</sub> ratio is not consistent with the measured ratio unless a large (unphysical) deposition rate  $> 2 \text{ hr}^{-1}$  is assumed, and 3) the differences between model and measurement in indoor PM<sub>2.5</sub> are likely due to loss of volatile ammonium-nitrate aerosol. We conclude that nitrate particle volatilization must be included in the model formulation.

Fischer, M. L., Price, P. N., Thatcher, T. L., Schwalbe, C. A., Craig, M. J., Wood, E. E., Sextro, R. G., and Gadgil, A. J., "Rapid Measurement and Mapping of Tracer Gas Concentrations in a Large Indoor Space." *Atmospheric Environment*, Vol. 35 (2001) pp. 2837-2844 . LBNL-45542.

#### ABSTRACT

Rapid mapping of gas concentrations in air benefits studies of atmospheric phenomena ranging from pollutant dispersion to surface layer meteorology. Here we demonstrate a technique that combines multiple-open-path tunable-diode-laser (TDL) spectroscopy and computed tomography to map tracer gas concentrations with approximately 0.5 m spatial and 7 second temporal resolution. Releasing CH<sub>4</sub> in a large (7m x 9m x 11m high) ventilated chamber, we measured path-integrated CH<sub>4</sub> concentrations over a planar array of 28 "long" (2-10 m) optical paths, recording a complete sequence of measurements every 7 seconds during the course of hour-long experiments. Maps of CH<sub>4</sub> concentration were reconstructed from the long-path data and compared with simultaneous measurements from 28 "short" (0.5 m) optical paths. On average, the reconstructed maps capture ~ 74% of the variance in the short path measurements. The accuracy of the reconstructed maps is limited, in large part, by the number of optical paths and the time required for the measurement. Straightforward enhancements to the instrumentation will allow rapid mapping of three-dimensional gas concentrations in indoor and outdoor air, with sub-second temporal resolution.

Fisk, W.J., G. Brager, H. Burge, J. Cummings, H. Levin, V. Loftness, M.J. Mendell, A. Persily, S. Taylor, and J.S. Zhang. "Energy-related indoor environmental quality research: A priority agenda". 2002. LBNL-51328.

#### ABSTRACT

A multidisciplinary team of IEQ and energy researchers has defined a program of priority energy-related IEQ research. This paper describes the methods employed to develop the agenda, and 35 high priority research and development (R&D) project areas related to four broad goals:

- 1) identifying IEQ problems and opportunities;
- 2) developing and evaluating energy-efficient technologies for improving IEQ;
- 3) developing and evaluating energy-efficient practices for improving IEQ; and
- 4) encouraging or assisting the implementation of technologies or practices for improving IEQ.

The identified R&D priorities reflect a strong need to benchmark IEQ conditions in small commercial buildings, schools, and residences. The R&D priorities also reflect the need to better understand how people are affected by IEQ conditions and by the related building characteristics and operation and maintenance practices. The associated research findings will provide a clearer definition of acceptable IEQ that is required to guide the development of technologies, practices, standards, and guidelines. Quantifying the effects of building characteristics and practices on IEQ conditions, in order to provide the basis for development of energy efficient and effective IEQ control measures, was also considered a priority. The development or advancement in a broad range of IEQ tools, technologies, and practices are also a major component of the priority research agenda.

Consistent with the focus on “energy-related” research priorities, building ventilation and heating, ventilating and air conditioning (HVAC) systems and processes are very prominent in the agenda. Research related to moisture and microbiological problems, particularly within hot and humid climates, is also prominent within the agenda. The agenda tends to emphasize research on residences, *small* commercial buildings, and schools because these types of buildings have been underrepresented in prior research. Most of the research areas apply to both new construction and existing buildings.

Nearly all of the recommended priority R&D project areas include tasks intended to facilitate the communication and implementation of the research results. In addition, the priority agenda includes several projects specifically designed to facilitate or stimulate the use of existing energy-efficient technologies and practices for improving IEQ.

To assure that the research program continues to meet the needs of stakeholders and to facilitate the coordination of research among sponsors, the core team recommends an annual meeting attended by sponsors, a balanced group of stakeholders, and a selection of researchers implementing the agenda.

**Fisk, W.J. “How IAQ affects health, productivity”. *ASHRAE Journal*, May 2002, Vol. 44(N5):56,58-60. LBNL-51381.**

#### **Introduction**

This article, a summary of Fisk (2000a, 2000b), estimates the nationwide improvements in health and productivity potentially attainable by providing better indoor environmental quality (IEQ) in U.S. buildings. Estimates include the potential reductions in three categories of health effects, the associated economic benefits, and the potential direct improvements in productivity not mediated through health. Expected costs and benefits of improving IEQ are compared, with a brief discussion of energy implications.

**Fisk, W.J. and M.J. Mendell. "Ventilation rates and health". *ASHRAE Journal*, v.44, no.8 (2002): pp.56-58. LBNL-51382.**

#### **Introduction**

This article summarizes the review by Seppänen et al. (1999) of current literature on the relationship of ventilation rates and carbon dioxide concentrations in non-residential and non-industrial buildings (primarily offices) with the health of the building’s occupants and with the occupants’ perceptions of indoor air quality (IAQ). While ventilation rates do not directly affect occupant health or perception outcomes, they affect indoor environmental conditions including air pollutant concentrations that, in turn, may modify the occupants’ health or perceptions. The review aims to provide a better scientific basis for setting health-related ventilation standards. Space constraints prohibit a detailed description of both ventilation rate and carbon dioxide concentration studies; therefore, this summary focuses primarily on the ventilation rate studies.

**Fisk, W.J., Brager, G., Brook, M., Burge, H., Cole, J., Cummings, J., Levin, H., Loftness, V., Logee, T., Mendell, M.J., Persily, A., Taylor, S., Zhang, J. (2002) “A priority agenda for energy-related indoor environmental quality research”. *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 2, pp.984-989. Indoor Air 2002, Santa Cruz, CA. LBNL-50612.**

#### **ABSTRACT**

A multidisciplinary team of IEQ and energy researchers is working together to define a program of priority energy-related IEQ research. This paper describes the methods employed, ten high priority broad research and development (R&D) goals, and 34 high priority R&D project areas linked to these goals.

**Fisk, W.J., Price, P.N., Faulkner, D., Sullivan, D.P., Dibartolomeo, D., Federspiel, C., Liu, L. “Worker productivity and ventilation rate in a call center: analyses of time-series data for a group of workers.” LBNL-49356. Report**

#### **ABSTRACT**

In previous studies, increased ventilation rates and reduced indoor carbon dioxide concentrations have been associated with improvements in health at work and increased performance in work-related tasks. Very few studies have assessed whether ventilation rates influence performance of real work. This paper describes part one of a two-part analysis from a productivity study performed in a call center operated by a health maintenance organization. Outside air ventilation rates were manipulated, indoor air temperatures, humidities, and carbon dioxide concentrations were monitored, and worker performance data for advice nurses, with 30-minute

resolution, were analyzed via multivariate linear regression to look for an association of performance with building ventilation rate, or with indoor carbon dioxide concentration (which is related to ventilation rate per worker). Results suggest that the effect of ventilation rate on worker performance in this call center was very small (probably less than 1%) or nil, over most of the range of ventilation rate experienced during the study (roughly 12 L s<sup>-1</sup> to 48 L s<sup>-1</sup> per person). However, there is some evidence suggesting performance improvements of 2% or more when the ventilation rate per person is very high, as indicated by indoor CO<sub>2</sub> concentrations exceeding outdoor concentrations by less than 75 ppm.

**Fisk, W.J., Price, P.N., Faulkner, D., Sullivan, D.P., Dibartolomeo, D., Federspiel, C., Liu, L., Lahiff, M. Worker Performance and ventilation: analysis of time-series data for a group of call-center workers, *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 1, pp.790-795. Indoor Air 2002, Santa Cruz, CA. LBNL-51724.**

#### **ABSTRACT**

We investigated the relationship of ventilation rates with the performance of advice nurses working in a call center. Ventilation rates were manipulated; temperatures, humidities, and CO<sub>2</sub> concentrations were monitored; and worker performance data, with 30-minute resolution, were collected. Multivariate linear regression was used to investigate the association of worker performance with building ventilation rate, or with indoor CO<sub>2</sub> concentration (which is related to ventilation rate per worker). Results suggest that the effect of ventilation rate on worker performance in this call center was very small (probably less than 1%) or nil, over most of the range of ventilation rate (roughly 12 L s<sup>-1</sup> to 48 L s<sup>-1</sup> per person). However, there is some evidence of worker performance improvements of 2% or more when the ventilation rate per person was very high, as indicated by the indoor CO<sub>2</sub> concentration exceeding the outdoor concentration by less than 75 ppm.

**Fisk WJ, Faulkner D, Palonen J, and Seppanen O (2002) Performance and cost of particle air filtration technologies, *Indoor Air*, 12(4):223-234. LBNL-47833.**

#### **ABSTRACT**

This paper predicts the reductions in the indoor mass concentrations of particles attainable from use of filters in building supply airstreams and also from use of stand-alone fan-filter units. Filters with a wide efficiency range are considered. Predicted concentration reductions are provided for indoor-generated particles containing dust mite and cat allergen, for environmental tobacco smoke particles, and for outdoor-air fine mode particles. Additionally, this paper uses a simple model and available data to estimate the energy and total costs of the filtration options. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 80%. To obtain substantial, e.g., 50%, reductions in indoor concentrations of these allergens, the rate of airflow through the filter must be at least a few indoor volumes per hour. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies and flow rates. Increasing the filter efficiency above ASHRAE 85% results in only modest predicted incremental decreases in indoor concentration. Energy costs and total costs can be similar for filtration using filters with a wide range of efficiency ratings. Total estimated filtration costs of approximately \$0.70 to \$1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

**Gadgil, A.J., C. Lobscheid and M.O. Abadie. Indoor pollutant mixing time in an isothermal closed room: An investigation using CFD. LBNL-51413.**

#### **ABSTRACT**

We report computational fluid dynamics (CFD) predictions of mixing time of a point pulse release of a pollutant in an unventilated mechanically mixed isothermal room. The aims of the study are to determine (1) the adequacy of the standard RANS two-equation (k-ε) turbulence model to predict the mixing times under these conditions, and (2) the extent to which the mixing time is a feature of the room airflow, rather than the source location within the room. CFD simulations modeled the twelve mixing time experiments performed by Drescher et al. (1995) in an isothermal sealed room for a point pulse release. Predictions of mixing time were found in good agreement with experimental measurements, over an order of magnitude variation in blower power. Additional CFD simulations were performed to investigate the relation between pollutant mixing time and pollutant source location. Seventeen source locations were investigated for five different blower power configurations in the room. Results clearly show large dependence of the mixing time on the room airflow, with some dependence on source location. We further explore dependence of mixing time on the local airflow

properties (velocity and turbulence intensity) at the source location. Implications for our findings for positioning air-toxic sensors in rooms are also discussed.

**Goth-Goldstein, R., M.L. Russell, B. Parimoo, and E.H. Weyand. "7H-Benzo[c]fluorene DNA adduct formation in different human cells in culture". LBNL-50479.**

#### **ABSTRACT**

7H-Benzo[c]fluorene (B[c]F) has been known for a long time as a component of complex mixtures such as coal tar or cigarette smoke. B[c]F has been identified recently as a potent lung tumorigen and a major DNA adduct-forming component of coal tar. We have investigated if human cells have the ability to form B[c]F:DNA adducts as detected in lungs of mice treated with B[c]F. MCF7 (human breast cancer), HepG2 (hepatoma) and Caco-2 (colon adenocarcinoma) cells were treated with increasing concentrations (0.2 - 10 µg/ml) of B[c]F for 20 hours. Adduct formation was evaluated using <sup>32</sup>P-postlabeling. A dose response in DNA adduct formation was detected in all three cell lines. In MCF7 and HepG2 cells, two adducts were detected, one of them corresponded to an adduct observed in the lungs of mice treated with B[c]F. This adduct is derived from 3-hydroxy B[c]F while the second, slower migrating adduct, appears to be unique to human cells. In contrast, Caco-2 cells formed at least four adducts. Two of the three most predominant adducts correspond to the two adducts observed in MCF7 and HepG2 cells while the additional predominate and a minor adduct are derived from 3,4-dihydrodiol B[c]F. The adducts derived from 3,4-dihydrodiol B[c]F are similar to those observed in mouse lung and skin. The detection of B[c]F:DNA adducts clearly demonstrates that human cells have the capacity to metabolically activate B[c]F to derivatives that covalently modify DNA. Similarities in the types of B[c]F:DNA adducts detected also demonstrates that B[c]F activation is similar in both human cells and mouse tissue.

**Gundel, L.A.; Sullivan, D.P.; Katsapov, G.Y.; Fisk, W.J. *A Pilot Study Of Energy Efficient Air Cleaning For Ozone*, Formal Report. LBNL-51836**

#### **ABSTRACT**

This report explores the feasibility of energy efficient low cost ozone removal from indoor air by examining carbon-based filtration options. Several candidate carbon-based materials and configurations were assessed by review of previous work and performance calculations. In addition, a laboratory pilot study was undertaken with the material that showed the most potential promise. This material was a commercially available filter that contained a thin layer of small activated carbon particles in a pleated configuration. For three months ozone ( $113 \pm 13$  ppm) in particle-filtered ambient air passed through the filter at a realistic ventilation system face velocity of  $0.5 \text{ m s}^{-1}$ . Ozone was injected upstream of the filter, and its concentration was monitored continuously upstream and downstream of the filter, as well as in the incoming ambient air. Throughout the three-month period, continuous measurements were made of the ambient temperature and humidity, as well as flow rate and pressure drop through the filter. The ozone removal efficiency was initially 96% and remained at 50% or higher for two and a half months. The estimated ozone removal capacity, before the efficiency dropped below 50%, was 0.3 g ozone per gram carbon. The pressure drop of the air flowing through the ozone filter was 26 Pa. Based on the size, efficiency, measured lifetime, and pressure drop of the ozone filter, it appears that ozone air cleaning may be practical in commercial air handling systems.

**Heath, G.A, Mendell, M.J. (2002) "Do Indoor Environments in Schools Influence Student Performance? A Review of the Literature". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 1, pp. 802-807. Indoor Air 2002, Santa Cruz, CA. LBNL-49567.**

#### **ABSTRACT**

The goal of this paper was to critically review available evidence on relationships between indoor environmental quality (IEQ) in schools and student performance. Because available evidence from schools was limited, the review expanded to include studies on direct relationships between the performance of children and adults and the indoor environments in schools, workplaces, residences, and controlled laboratory settings. The most persuasive available evidence suggests that some aspects of IEQ, including low ventilation rate and less daylight or light, may reduce the performance of occupants, including students in schools. Other evidence identifies additional possible influences, such as pollen and some carpets. Substantial limitations in the quantity and quality of available research findings suggest many questions for future study. Sufficient evidence is available to justify (1) actions to safeguard IEQ in schools and (2) the conduct of focused, well-designed research to help guide future policies and actions regarding IEQ in schools.

Hering, S.V, Lunden, M.M, Kirchstetter, T.W, Thatcher, T.L, Revzan, K.L, Sextro, R.G, Brown, N.J, Watson, J. Chow, J. "Indoor, Outdoor And Regional Profiles Of Pm<sub>2.5</sub> Sulfate, Nitrate And Carbon". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 1, pp. 874-879. Indoor Air 2002, Santa Cruz, CA. LBNL-49980.

#### ABSTRACT

Fine particle concentrations were measured simultaneously at three locations: a regional monitoring site in Fresno, California, a backyard of an unoccupied residence in Clovis, California located 6 km northeast of the regional site; and indoors at the same residence. Measurements included 10-min determination of PM<sub>2.5</sub> nitrate, sulfate and carbon using an automated collection and vaporization system, and black carbon measured by light attenuation through a filter deposit. Specific outdoor PM<sub>2.5</sub> constituents were compared to assess the appropriateness of using regional data to model indoor concentrations from outdoor sources. The outdoor data show that, in general, the regional results provide a good representation of the concentrations seen at the building exterior. The indoor concentrations showed considerable attenuation as well as a broadening and time-lag for the concentration peaks. The concentration reduction was the largest for PM<sub>2.5</sub> nitrate, which appears to undergo phase changes in addition to indoor deposition and penetration losses.

Hodgson, A.T, Faulkner, D., Sullivan, D.P., DiBartolomeo, D.L., Russell, M.L., Fisk, W.J. (2002) "Effect of outside air ventilation rate on VOC concentrations and emissions in a call center *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 2, pp. 168-173. Indoor Air 2002, Santa Cruz, CA. LBNL-49535.

#### ABSTRACT

A study of the relationship between outside air ventilation rate and concentrations of VOCs generated indoors was conducted in a call center. Ventilation rates were manipulated in the building's four air handling units (AHUs). Concentrations of VOCs in the AHU returns were measured on 7 days during a 13-week period. Indoor minus outdoor concentrations and emission factors were calculated. The emission factor data was subjected to principal component analysis to identify groups of co-varying compounds based on source type. One vector represented emissions of solvents from cleaning products. Another vector identified occupant sources. Direct relationships between ventilation rate and concentrations were not observed for most of the abundant VOCs. This result emphasizes the importance of source control measures for limiting VOC concentrations in buildings.

Hodgson, A.T., Apte, M.G., Shendell, D.G., Beal, D., McIlvaine, J.E.R. (2002) "Implementation of VOC Source Reduction Practices in a Manufactured House and in School Classrooms," *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 3, pp. 576-581. Indoor Air 2002, Santa Cruz, CA. LBNL-49536.

#### ABSTRACT

Detailed studies of a new manufactured house and four new industrialized relocatable school classrooms were conducted to determine the emission sources of formaldehyde and other VOCs and to identify and implement source reduction practices. Procedures were developed to generate VOC emission factors that allowed reasonably accurate predictions of indoor air VOC concentrations. Based on the identified sources of formaldehyde and other aldehydes, practices were developed to reduce the concentrations of these compounds in new house construction. An alternate ceiling panel reduced formaldehyde concentrations in the classrooms. Overall, the classrooms had relatively low VOC concentrations.

Hodgson, A.T., Beal, D. and McIlvaine, J.E.R. (In press) Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house. *Indoor Air* (accepted for publication). LBNL-47627. Previously reported as submitted.

#### ABSTRACT

Formaldehyde, less-volatile aldehydes, and terpene hydrocarbons are generally the predominant air contaminants in new manufactured and site-built houses. This study was conducted to identify the major sources of these compounds in a typically constructed, new manufactured house. Specimens of materials used within the house envelope were collected from the production facility. These were individually preconditioned for  $19 \pm 4$  days and tested for emissions of formaldehyde and the other target compounds using small-scale chambers. Several cabinetry materials, passage doors and the plywood subfloor were the predominant sources of formaldehyde and other aldehydes. The plywood subfloor was the predominant terpene source. Whole-house emission rates for combined materials were predicted based on the emission factors and the corresponding material quantities. These predicted rates were compared to whole-house emission rates calculated from measurements made at the house three months after its installation. For 11 of 14 target compounds including formaldehyde, the predicted and calculated rates were within a factor of two. This

generally good agreement indicates that the predominant sources were correctly accounted for. Based on these results, practices are proposed for reducing the concentrations of the target compounds in newly constructed houses.

**Holman, H.Y., Goth-Goldstein, R., Aaston, D., Mao, Y., and Kengsoontra, J. (2002) Evaluation of gastrointestinal solubilization of petroleum hydrocarbon residues in soil using an *in vitro* physiologically-based model. *Env. Science & Tech.*, 36: 1281-1286. (LBNL-48401). No Abstract available.**

**IED Staff. A compilation of papers for the Indoor Air 2002 Conference in memory of Joan M. Daisey. (2002). LBNL-50419. No Abstract available.**

**Klepeis, N.E. and W.W. Nazaroff. "Characterizing size-specific ETS particle emissions". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 2, pp. 162-167. Indoor Air 2002, Santa Cruz, CA. LBNL-50938.**

#### **ABSTRACT**

We report a method for estimating the size distribution of particle emissions from indoor sources. The method is applied to concentration data from a series of cigar and cigarette experiments to characterize environmental tobacco smoke particles. The method incorporates a particle dynamics model, which provided good fits to observed concentrations when using, as input, optimal values of mass emission rate and deposition velocity for each particle size range. The optimal particle emissions were fit to log-normal distributions, yielding mass median diameters of approximately 0.2  $\mu$ m and an average geometric standard deviation of 2.3. The total particle emissions obtained by integrating the empirical size distribution were 0.2 - 0.7 mg/min for cigars and 0.7 - 0.9 mg/min for cigarettes. The measurements of particle size characteristics agree well with prior research, but the integrated mass measurements are consistently lower than those determined from filter-based measurements.

**Klepeis, N., M. Apte, L. Gundel, R.G. Sextro, and W.W. Nazaroff. "Determining size-specific emission factors for environmental tobacco smoke particles". Submitted to *Aerosol Science and Technology* (September, 2002). LBNL-51049.**

#### **ABSTRACT**

Because size is a major controlling factor for indoor airborne particle behavior, human particle exposure assessments will benefit from improved knowledge of size-specific particle emissions. We report a method of inferring size-specific mass emission factors for indoor sources that makes use of an indoor aerosol dynamics model, measured particle concentration time series data, and an optimization routine. This approach provides – in addition to estimates of the emissions size distribution and integrated emission factors – estimates of deposition rate, an enhanced understanding of particle dynamics, and information about model performance. We applied the method to size-specific environmental tobacco smoke (ETS) particle concentrations measured every minute with an 8-channel optical particle counter (PMS-LASAIR; 0.1-2+ micrometer diameters) and every 10 or 30 min with a 34-channel differential mobility particle sizer (TSI-DMPS; 0.01-1+ micrometer diameters) after a single cigarette or cigar was machine-smoked inside a low air-exchange rate 20m<sup>3</sup> chamber. The aerosol dynamics model provided good fits to observed concentrations when using optimized values of mass emission rate and deposition rate for each particle size range as input. Small discrepancies observed in the first 1-2 hours after smoking are likely due to the effect of particle evaporation, a process neglected by the model. Size-specific ETS particle emission factors were fit with log-normal distributions, yielding an average mass median diameter of 0.2 micrometers and an average geometric standard deviation of 2.3 with no systematic differences between cigars and cigarettes. The equivalent total particle emission rate, obtained by integrating each size distribution, was 0.2-0.7 mg/min for cigars and 0.7-0.9 mg/min for cigarettes.

**Kumar, Satish and William J. Fisk. "IEQ and the impact on building occupants". *ASHRAE Journal*, v.44, no.4 (2002): pp.50-52. LBNL-51288.**

#### **Introduction**

Research into indoor environmental quality (IEQ) and its effects on health, comfort, and performance of occupants is becoming an increasing priority as interest in high performance buildings and organizational productivity grows. Facility managers are interested in IEQ's close relationship to energy use in facilities. Employers, by providing excellent indoor environments, hope to enhance employee comfort and productivity, reduce absenteeism and health care costs, and reduce risk of litigation. The increasing interest in this field has put additional pressure on the research community as architects, engineers, facility managers, building

investors, health officials, jurists, and the public seek practical guidelines on creating a safe, healthy, and comfortable indoor environment.

Research on the relationships of IEQ to the health, comfort, and productivity of occupants has advanced considerably within the last decade. One of the primary goals of the Indoor Health and Productivity (IHP) Project is to communicate the results of this research, currently reported primarily in research publications, to building professionals. Consequently, the IHP project has worked with a peer review panel to select five key IHP papers and prepare summaries of these papers for publication in ASHRAE Journal.

This article precedes those five summary articles, which will appear in the next five issues of the journal. This article summarizes the methodology employed to select the five papers, briefly summarizes the message of each paper, and discusses the practical implications for architects and engineers.

More information about the objectives of the IHP project, results of research conducted under this project, and project sponsors and partners can be found at [www.IHPCentral.org](http://www.IHPCentral.org). The web site also has an online bibliography of approximately 900 papers on the topic of indoor health and productivity, drawn primarily from approximately 100 leading international journals and international conferences.

**Kumar, Satish and William J. Fisk. "IEQ and the impact on employee sick leave". ASHRAE Journal, v.44, no.7 (2002): pp.97-98. LBNL-51289.**

#### **Introduction**

When selecting minimum ventilation rates, employers need to strike a balance between the well-recognized energy costs of providing higher minimum ventilation rates and the expected, but less well quantified, health benefits from higher rate of ventilation. This is a summary of the paper by Milton et al. (2000) that found low employee sick leave associated with high ventilation rates in a set of buildings located in Massachusetts. A simple cost-benefit analysis is also presented.

**Kumar, S., Fisk, W.J., *The role of Emerging Energy-Efficient Technology in Promoting Workplace Productivity and Health: Final Report.* (2002). LBNL-49706.**

#### **Introduction**

When selecting minimum ventilation rates, employers need to strike a balance between the well-recognized energy costs of providing higher minimum ventilation rates and the expected, but less well quantified, health benefits from higher rate of ventilation. This is a summary of the paper by Milton et al. (2000) that found low employee sick leave associated with high ventilation rates in a set of buildings located in Massachusetts. A simple cost-benefit analysis is also presented.

**Liu, D.L., Nazaroff, W.W. (2002) "Particle Penetration Through Windows". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol.1, pp. 862-867. Indoor Air 2002, Santa Cruz, CA. No LBNL Number.**

#### **ABSTRACT**

This study aims to characterize the fractional penetration of airborne particles through windows, one of the important sites of air leakage through building envelopes. Two aluminum windows were evaluated, one with weatherstripping and one without. For each experiment, a finished window was mounted and sealed in a plywood panel that separated two well-mixed compartments. A small pressure difference was established between the compartments to induce a constant rate of airflow through leakage paths in the window. Particles were injected into one chamber and their concentrations were measured in both chambers. Two methods were employed to evaluate the size-resolved particle penetration: a steady-state method and a dynamic, concentration growth method. The results indicate that airborne particles of 0.2 to 3  $\mu\text{m}$  penetrate through both test windows fairly effectively, while significant particle losses are observed for particles smaller and larger than this range.

**Lobscheid, C., Gadgil, (2002) "Mixing of a point-source indoor pollution: Numerical predictions and comparison with experiments". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 4, pp. 223-228. Indoor Air 2002, Santa Cruz, CA. LBNL-49457.**

## ABSTRACT

In most practical estimates of indoor pollutant exposures, it is common to assume that the pollutant is uniformly and instantaneously mixed in the indoor space. It is also commonly known that this assumption is simplistic, particularly for point sources, and for short-term or localized indoor exposures.

We report computational fluid dynamics (CFD) predictions of mixing time of a point-pulse release of a pollutant in an unventilated mechanically mixed isothermal room. We aimed to determine the adequacy of the standard RANS two-equation ( $k$ - $\epsilon$ ) turbulence model to predict the mixing times under these conditions. The predictions were made for the twelve mixing time experiments performed by Drescher et al. (1995). We paid attention to adequate grid resolution, suppression of numerical diffusion, and careful simulation of the mechanical blowers used in the experiments. We found that the predictions are in good agreement with experimental measurements.

**Lorenzetti, D.M. (2002) "Assessing multizone airflow software". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 1, pp. 267-271. Indoor Air 2002, Santa Cruz, CA. LBNL-47653.**

## ABSTRACT

Several standard multizone modeling programs, in order to improve their computational efficiency, make a number of simplifying assumptions. This paper examines how those assumptions reduce the solution times and memory use of the programs, but at the cost of restricting the models they can express. Applications where these restrictions may adversely affect the program's usefulness include: (1) natural ventilation, when buoyancy effects dominate mechanically-driven flow; (2) duct system design, when losses in T-junctions affect the system performance; and (3) control system design, when the dynamic transport of pollutants plays a significant role in the simulated system.

**Lunden, M.M., Thatcher, T.L., Littlejohn, D., Fischer, M.L., Hering, S.V., Sextro, R.G., Brown, N.J. (2002) "The Transformation Of Outdoor Ammonium Nitrate Aerosols In The Indoor Environment". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 5, pp. 74-79. Indoor Air 2002, Santa Cruz, CA. LBNL-50158.**

## ABSTRACT

Recent studies associate particulate air pollution with adverse health effects; however, the exposure to indoor particles of outdoor origin is not well characterized, particularly for individual chemical species. In response to this, a field study in an unoccupied, single-story residence in Clovis, California has been conducted. Real-time particle monitors were used both outdoors and indoors to quantify PM<sub>2.5</sub> nitrate, sulfate, and carbon. The results show that reduced indoor sulfate and carbon levels are primarily due to deposition and penetration losses. However, measured indoor ammonium nitrate levels were often observed to be at significantly lower levels than expected based solely on penetration and deposition losses. The additional reduction appears to be due to the transformation of ammonium nitrate into ammonia and nitric acid indoors, which are subsequently lost by deposition and sorption to indoor surfaces. The size of the effect is dependent upon factors such as temperature, relative humidity, and ventilation rate.

**Maddalena, R.L., T.E. McKone and N.Y. Kado. "Exposure chamber measurements of mass transfer and partitioning at the plant/air interface". *Environmental Science & Technology*, v.36; no.16; pp.3577-3585; August 15, 2002. LBNL-50569.**

## ABSTRACT

Dynamic measures of air and vegetation concentrations in an exposure chamber and a two-box mass balance model are used to quantify factors that control the rate and extent of chemical partitioning between vegetation and the atmosphere. A continuous stirred flow-through exposure chamber was used to investigate the gas-phase transfer of pollutants between air and plants. A probabilistic two-compartment mass-balance model of plant/air exchange within the exposure chamber was developed and used with measured concentrations from the chamber to simultaneously evaluate partitioning ( $K_{pa}$ ), overall mass transfer across the plant/air interface ( $U_{pa}$ ) and loss rates in the atmosphere ( $R_a$ ) and aboveground vegetation ( $R_p$ ). The approach is demonstrated using mature *Capsicum annuum* (bell pepper) plants exposed to phenanthrene (PH), anthracene (AN), fluoranthene (FL) and pyrene (PY). Measured values of  $\log K_{pa} (V_{\text{air}}/V_{\text{fresh plant}})$  were 5.7, 5.7, 6.0 and 6.2 for PH, AN, FL and PY, respectively. Values of  $U_{pa} (\text{m d}^{-1})$  under the conditions of this study ranged from 42 for PH to 119 for FL. After correcting for wall effects, the estimated reaction half-lives in air were 3, 9 and 25 hours for AN, FL and PY. Reaction half-lives in the plant compartment were 17, 6, 17 and 5 days for PH, AN, FL and PY. The combined use of exposure chamber measurements and models provides a robust tool for simultaneously



measuring several different transfer factors that are important for modeling the uptake of pollutants into vegetation.

**MacLeod, M., D.G. Woodfine, D. Mackay, T.E. McKone, D.H. Bennett, and R.L. Maddalena. "BETR North America: A regionally segmented multimedia contaminant fate model for North America". *Environmental Science & Pollution Research*, v.8; no.3; pp.156-163; 2001. LBNL-50571.**

#### **ABSTRACT**

We present the Berkeley-Trent North American contaminant fate model (BETR North America), a regionally segmented multimedia contaminant fate model based on the fugacity concept. The model is built on a framework that links contaminant fate models of individual regions, and is generally applicable to large, spatially heterogeneous areas. The North American environment is modeled as 24 ecological regions, within each region contaminant fate is described using a 7 compartment multimedia fugacity model including a vertically segmented atmosphere, freshwater, freshwater sediment, soil, coastal water and vegetation compartments. Inter-regional transport of contaminants in the atmosphere, freshwater and coastal water is described using a database of hydrological and meteorological data compiled with Geographical Information Systems (GIS) techniques. Steady-state and dynamic solutions to the 168 mass balance equations that make up the linked model for North America are discussed, and an illustrative case study of toxaphene transport from the southern United States to the Great Lakes Basin is presented. Regionally segmented models such as BETR North America can provide a critical link between evaluative models of long-range transport potential and contaminant concentrations observed in remote regions. The continent-scale mass balance calculated by the model provides a sound basis for evaluating long-range transport potential of organic pollutants, and formulation of continent scale management and regulatory strategies for chemicals.

**Matson, N.E., Wray, C.P., Walker, I.S., and Sherman, M.H. (2002) *Potential Benefits of Commissioning California Homes*. LBNL-48258. No Abstract Available.**

**Marshall, Julian. (2002) *Exposure to Motor Vehicle Emissions: An Intake Fraction Approach*, Master's Thesis. LBNL-51854**

#### **ABSTRACT**

Motor vehicles are a significant source of population exposure to air pollution. Focusing on California's South Coast Air Basin as a case study, I combine ambient monitoring station data with hourly time-activity patterns to determine the population intake of motor vehicle emissions during 1996 – 1999. Three microenvironments are considered wherein the exposure to motor vehicle emissions is higher than in ambient air: in and near vehicles, inside a building that is near a freeway, and inside a residence with an attached garage. Total motor vehicle emissions are taken from the EMFAC model. The 15 million people in the South Coast inhale 0.0048% of primary, nonreactive compounds emitted into the basin by motor vehicles. Intake of motor vehicle emissions is 46% higher than the average ambient concentration times the average breathing rate, because of microenvironments and because of temporal and spatial correlation among breathing rates, concentrations, and population densities.

Intake fraction (iF) summarizes the emissions-to-intake relationship as the ratio of population intake to total emissions. iF is a population level exposure metric that incorporates spatial, temporal, and interindividual variability in exposures. iFs can facilitate the calculation of population exposures by distilling complex emissions-transport-receptor relationships. I demonstrate this point by predicting the population intake of various primary gaseous emissions from motor vehicles, based on the intake fraction for benzene and carbon monoxide.

**McKone, T.E., Thatcher, T.L., Fisk, W.J., Sextro, R.G., Sohn, M.D., Delp, W.W., Riley, W.J. (2002) "Factors affecting the concentration of outdoor particles indoors: existing data and data needs". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 1, pp. 176-181. Indoor Air 2002, Santa Cruz, CA. LBNL-49570.**

#### **ABSTRACT**

Accurate characterization of particle concentrations indoors is critical to exposure assessments. It is estimated that indoor particle concentrations depend strongly on outdoor concentrations. For health scientists, knowledge of the factors that control the relationship of indoor particle concentrations to outdoor levels is particularly important. In this paper, we identify and evaluate sources of data for those factors that affect the transport to and concentration of outdoor particles indoors. To achieve this goal, we (i) identify and assemble relevant information on how particle behavior during air leakage, HVAC operation, and particle filtration effects indoor particle concentration; (ii) review and evaluate the assembled information to distinguish data that are directly

relevant to specific estimates of particle transport from those that are only indirectly useful; and (iii) provide a synthesis of the currently available information on building air-leakage parameters and their effect on indoor particle matter concentrations.

**McKone, T.E. and D.H. Bennett. "Chemical-specific representation of air-soil exchange and soil penetration in regional multimedia models". *Environmental Science & Technology*, (accepted for publication; December, 2002. LBNL-46693.**

#### **ABSTRACT**

In multimedia mass-balance models, the soil compartment is an important sink as well as a conduit for transfers to vegetation and shallow groundwater. Here a novel approach for constructing soil transport algorithms for multimedia fate models is developed and evaluated. The resulting algorithms account for diffusion in gas and liquid components; advection in gas, liquid, or solid phases; and multiple transformation processes. They also provide an explicit quantification of the characteristic soil penetration depth. We construct a compartment model using three and four soil layers to replicate with high reliability the flux and mass distribution obtained from the exact analytical solution describing the transient dispersion, advection, and transformation of chemicals in soil layers with different properties but a boundary condition at the air-soil surface. The soil compartment algorithms can be dynamically linked to other compartments (air, vegetation, ground water, surface water) in multimedia fate models. We demonstrate and evaluate the performance of the algorithms in a model with applications to benzene, benzo(a)pyrene, MTBE, TCDD, and tritium.

**McWilliams, Jennifer and Max Sherman. Review of air flow measurement techniques. LBNL-49747. No Abstract available.**

**Mendell, M.J., G.M. Naco, T.G. Wilcox, W.K. Sieber. (2002) "Building-related risk factors and work-related lower respiratory symptoms in 80 office building". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 1, pp. 103-108. Indoor Air 2002, Santa Cruz, CA. LBNL-49566.**

#### **ABSTRACT**

We assessed building-related risk factors for lower respiratory symptoms in office workers. The National Institute for Occupational Safety and Health in 1993 collected data during indoor environmental health investigations of workplaces. We used multivariate logistic regression analyses to assess relationships between lower respiratory symptoms in office workers and risk factors plausibly related to microbiologic contamination. Among 2,435 occupants in 80 office buildings, frequent, work-related multiple lower respiratory symptoms were strongly associated, in multivariate models, with two risk factors for microbiologic contamination: poor pan drainage under cooling coils and debris in outside air intake. Associations tended to be stronger among those with a history of physician-diagnosed asthma. These findings suggest that adverse lower respiratory health effects from indoor work environments, although unusual, may occur in relation to poorly designed or maintained ventilation systems, particularly among previously diagnosed asthmatics. These findings require confirmation in more representative buildings.

**Mendell, M.J., Fisk, W.J., Petersen, M.R., Hines, C.J., Dong, M., Faulkner, D., Deddens, J.A., Ruder, A.M., Sullivan, D.P., Boeniger, M.F. (2002) "Indoor Particles and Symptoms Among Office Workers: Results from a Double-Blind Cross-Over Study". *Epidemiology* 13:296-304. LBNL-48217.**

#### **ABSTRACT**

##### **Background**

We studied the effects of removing small airborne particles in an office building without unusual contaminant sources or occupant complaints.

##### **Methods**

We conducted a double-blind crossover study of enhanced particle filtration in an office building in the Midwest U.S. in 1993. We replaced standard particle filters, in separate ventilation systems on two floors, with highly efficient filters, on alternate floors weekly over four weeks. Repeated-measures models were used to analyze data from weekly worker questionnaires and multiple environmental measurements.

##### **Results**

Bioaerosol concentrations were low. Enhanced filtration reduced concentrations of the smallest airborne particles by 94%. This reduction was not associated with reduced symptoms among the 396 respondents, but three performance-related mental states improved; for example, the confusion scale decreased (-3.7%; 95% confidence limits (CL) = -6.5, -0.9). Most environmental dissatisfaction variables also improved; eg, "stuffy"

air, -5.3% (95% CL = -10.3, -0.4). Cooler temperatures within the recommended comfort range were associated with remarkably large improvement in most outcomes; for example, per 1°C decrease, chest tightness decreased -23.4% (95% CL = -38.1, -8.7).

#### **Conclusions**

Benefits of enhanced filtration require assessment in buildings with higher particulate contaminant levels, in studies controlling for temperature effects. Benefits from lower indoor temperatures need confirmation.

**Mora, L. and A.J. Gadgil. Theoretical study of pollutant mixing in rooms induced by occupancy. LBNL-49730. No Abstract available.**

**Nazaroff, W.W. and B.C. Singer. "Inhalation of hazardous air pollutants from environmental tobacco smoke in US residences". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 2, pp. 477-482. Indoor Air 2002, Santa Cruz, CA. LBNL-50878.**

#### **ABSTRACT**

In the United States, 48 million adults smoke  $5 \times 10^{11}$  cigarettes per year. Many cigarettes are smoked in private residences causing regular environmental tobacco smoke (ETS) exposure to at least 31 million nonsmokers (11% of the US population), including 16 million juveniles. ETS contains many chemical species whose industrial emissions are regulated by the US federal government as hazardous air pollutants (HAPs). In this paper, average daily residential exposures to 15 HAPs in ETS are estimated for US nonsmokers who live with smokers. The evaluation is based on material-balance modeling, and utilizes published data on smoking habits, demographics, and housing. Newly measured exposure-relevant emission factors are incorporated. Comparison of exposure concentration estimates with health-based guidelines for chronic exposure suggests that aldehydes — specifically acrolein, acetaldehyde, and formaldehyde — should be of particular concern in ETS. Cumulative population intake results are compared for these compounds against other sources of exposure.

**Pang, Yanbo, Lara A. Gundel, Timothy Larson, Dennis Finn, L.J. Sally Liu, and Candis S. Claiborn. "Development and evaluation of a novel personal particulate organic and mass sampler". Accepted for publication Environmental Science and Technology. LBNL-50850.**

#### **ABSTRACT**

Accurate measurement of personal exposure to particulate matter and its constituents requires samplers that are accurate, compact, lightweight, inexpensive and convenient to use. The Personal Particulate Organic and Mass Sampler (PPOMS) has been developed to meet these criteria. The PPOMS uses activated carbon-impregnated foam as a combined 2.5- $\mu$ m size-selective inlet and denuder for assessment of fine particle mass and organic carbon. Proof of the PPOMS concept has been established by comparing mass and organic carbon in particles collected with collocated samplers in Seattle, at a central outdoor site and in residences. Daily particulate mass concentrations averaged  $10.0 \pm 5.2$ ,  $12.0 \pm 5.3$ , and  $11.2 \pm 5.1 \mu\text{g m}^{-3}$  for the Federal Reference Method, the Harvard Personal Exposure Monitor, and the PPOMS, respectively, for 10 24-h sampling periods. During a series of  $\text{PM}_{2.5}$  indoor organic carbon (OC) measurements from single quartz filters, the apparent indoor OC averaged  $7.7 \pm 0.8 \mu\text{g of C m}^{-3}$ , which was close to the indoor  $\text{PM}_{2.5}$  mass from collocated Teflon filters ( $7.3 \pm 2.3 \mu\text{g of C m}^{-3}$ ), indicating the presence of a large positive OC artifact. In collocated measurements, the PPOMS eliminated this artifact just as well as the Integrated Gas and Particle Sampler that incorporated a macroreticular poly(styrene-divinylbenzene) (XAD-4) resin-coated denuder, yielding OC concentrations of  $2.5 \pm 0.4$  and  $2.4 \pm 1.0 \mu\text{g C m}^{-3}$ , respectively. Thermal analysis for OC indicated that the indoor positive artifact was due to adsorption of gas-phase SVOC. This study shows that the PPOMS design provides a 2.5- $\mu$ m size-selective inlet that also prevents the adsorption of gas-phase semi-volatile organic compounds onto quartz filters, thus eliminating the filter positive artifact. The PPOMS meets a significant current challenge for indoor and personal sampling of particulate organic carbon. The PPOMS design can also simplify accurate ambient sampling for  $\text{PM}_{2.5}$ .

**Price, Phillip N., David M. Lorenzetti, Ashok J. Gadgil, Michael D. Sohn, Woody Delp, and Sondra Jarvis. Information for first responders to a chemical or biological attack. LBNL/PUB-866. No Abstract available.**

**Price, Phillip N., Woody Delp, Michael D. Sohn, Tracy L. Thatcher, David M. Lorenzetti, Richard G. Sextro, Ashok G. Gadgil, Elisa Derby, and Sondra Jarvis. Advice for first responders to a building during a chemical or biological attack. LBNL/PUB-867. No Abstract available.**

**Prill, R., Fisk, W.J. "Long Term Performance of Radon mitigation systems". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 2, pp. 641-646. Indoor Air 2002, Santa Cruz, CA. LBNL-50041.**

#### **ABSTRACT**

Researchers installed radon mitigation systems in 12 houses in Spokane, Washington and Coeur d'Alene, Idaho during the heating season 1985 –1986 and continued to monitor indoor radon quarterly and annually for ten years. The mitigation systems included active sub-slab ventilation, basement over-pressurization, and crawlspace isolation and ventilation. The occupants reported various operational problems with these early mitigation systems. The long-term radon measurements were essential to track the effectiveness of the mitigation systems over time. All 12 homes were visited during the second year of the study, while a second set 5 homes was visited during the fifth year to determine the cause(s) of increased radon in the homes. During these visits, the mitigation systems were inspected and measurements of system performance were made. Maintenance and modifications were performed to improve system performance in these homes.

**Riley, W.J., T.E. McKone, A.C.K. Lai, and W.W. Nazaroff, "Indoor particulate matter of outdoor origin: importance of size-dependent removal mechanisms," *Environmental Science & Technology*, v.36; pp.200-207, 2002. LBNL-47437**

#### **ABSTRACT**

Adverse human health effects have been observed to correlate with levels of outdoor particulate matter (PM), even though most human exposure to PM of outdoor origin occurs indoors. In this study, we apply a model and empirical data to explore the indoor PM levels of outdoor origin for two major building types: offices and residences. Typical ventilation rates for each building type are obtained from the literature. Published data are combined with theoretical analyses to develop representative particle penetration coefficients, deposition loss rates, and ventilation-system filter efficiencies for a broad particle size range (i.e., 0.001-10  $\mu\text{m}$ ). We apply archetypal outdoor number, surface area, and mass PM size distributions for both urban and rural airsheds. We also use data on mass-weighted size distributions for specific chemical constituents of PM: sulfate and elemental carbon. Predictions of the size-resolved indoor proportion of outdoor particles (IPOP) for various conditions and ambient particle distributions are then computed. The IPOP depends strongly on the ambient particle size distribution, building type and operational parameters, and PM metric. We conclude that an accurate determination of exposure to particles of ambient origin requires explicit consideration of how removal processes in buildings vary with particle size.

**Russell, M.L., Goth-Goldstein, R., Apte, M.G., Fisk, W.J. (2002) "Method for measuring the size distribution of airborne rhinovirus". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 1, pp. 40-45. Indoor Air 2002, Santa Cruz, CA. LBNL-49574.**

#### **ABSTRACT**

About 50% of viral-induced respiratory illnesses are caused by the human rhinovirus (HRV). Measurements of the concentrations and sizes of bioaerosols are critical for research on building characteristics, aerosol transport, and mitigation measures. We developed a quantitative reverse transcription-coupled polymerase chain reaction (RT-PCR) assay for HRV and verified that this assay detects HRV in nasal lavage samples. A quantitation standard was used to determine a detection limit of 5 fg of HRV RNA with a linear range over 1000-fold. To measure the size distribution of HRV aerosols, volunteers with a head cold spent two hours in a ventilated research chamber. Airborne particles from the chamber were collected using an Andersen Six-Stage Cascade Impactor. Each stage of the impactor was analyzed by quantitative RT-PCR for HRV. For the first two volunteers with confirmed HRV infection, but with mild symptoms, we were unable to detect HRV on any stage of the impactor.

**Seppanen, O., Fisk, W.J. (2002) "Relationship of SBS-symptoms and ventilation system type in office buildings. *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 3, pp. 437-442. Indoor Air 2002, Santa Cruz, CA. LBNL-50046.**

#### **ABSTRACT**

This paper provides a summary of current knowledge about the associations of ventilation system types in office buildings with sick building syndrome symptoms. Most studies completed to date indicate that relative to natural ventilation, air conditioning, with or without humidification, was consistently associated with a statistically significant increase in the prevalence of one or more SBS symptoms, by approximately 30% to 200%. In two of three analyses from a single study (assessments), symptom prevalences were also significantly

higher in air-conditioned buildings than in buildings with simple mechanical ventilation and no humidification. The available data also suggest, with less consistency, an increase in risk of symptoms with simple mechanical ventilation relative to natural ventilation. The statistically significant associations of mechanical ventilation and air conditioning with SBS symptoms are much more frequent than expected from chance and also not likely to be a consequence of confounding by several potential personal, job, or building-related confounders. Multiple deficiencies in HVAC system design, construction, operation, or maintenance, including some of which cause pollutant emissions from HVAC systems, may contribute to the increases in symptom prevalences but other possible reasons remain unclear.

**Sextro, R.G., Lorenzetti, D.M., Sohn, M.D., Thatcher, T.L. (2002) "Modeling the spread of anthrax in buildings". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA. Vol. 4, pp. 506-511. Indoor Air 2002, Santa Cruz, CA. LBNL-49537.**

#### **ABSTRACT**

The recent contamination of several U.S. buildings by letters containing anthrax demonstrates the need to understand better the transport and fate of anthrax spores within buildings. We modeled the spread of anthrax for a hypothetical office suite and estimated the distribution of mass and resulting occupant exposures. Based on our modeling assumptions, more than 90% of the anthrax released remains in the building during the first 48 hours, with the largest fraction of the mass accumulating on floor surfaces where it is subject to tracking and resuspension. Although tracking and resuspension account for only a small amount of mass transfer, the model results suggests they can have an important effect on subsequent exposures. Additional research is necessary to understand and quantify these processes.

**Shendell, DG, Hodgson, AT, Lee, S-M, Apte, MG, Sullivan, DP, Hotchi, T, Fisk, WJ. "VOCs in New Relocatable Classrooms: Assessment of School-Day Exposures Comparing Interior Finish Materials and HVAC Systems." Poster presented at the joint annual meeting of the International Society of Exposure Analysis (12<sup>th</sup>) and the International Society of Environmental Epidemiology (14<sup>th</sup>), Vancouver, B.C., Canada, August 11-15, 2002. ABSTRACT published in *Epidemiology*, 13 (4), S143.**

The prevalence of relocatable classrooms (RCs) at schools is rising due to initiatives to reduce K-3 class size, and limited capital resources. Concerns regarding inadequate ventilation and indoor air quality in RCs have been raised. Since students and teachers spend the majority of a 7-8 hour school day inside classrooms, indoor contaminant concentrations are assumed to drive personal school-day exposures. We conducted a demonstration project in new relocatable classrooms (RCs) during the 2001-02 school year to address these issues. The benefits of upgrades including an energy efficient heating, ventilation, and air conditioning (HVAC) system and alternate interior finish materials were investigated. One specific goal was to demonstrate that improved ventilation coupled with source reduction could lower indoor concentrations of toxic and odorous volatile organic compounds (VOCs), including formaldehyde and acetaldehyde. Four new 24' x 40' (960 ft<sup>2</sup>) RCs were constructed and sited in pairs at an elementary school campus in each of two participant school districts (SD) in Northern California. Each RC was equipped with a standard HVAC system with intermittent 25-50% outdoor air ventilation and an energy-efficient advanced system providing continuous 100% ventilation (15 cfm/occupant). Alternate carpets, wall panels, and ceiling panels were installed in two classrooms—one in each pair—based on the results of a laboratory study of VOC emissions from standard and alternate materials. The two HVAC systems were operated on alternate weeks. School day-integrated air samples were collected indoors and outdoors mid-week during eight and nine weeks in the cooling (fall) and heating (winter) seasons, respectively. VOCs were collected on sorbent media and analyzed by thermal desorption GC/MS. Aldehydes were collected on DNPH treated silica gel cartridges and analyzed by HPLC. The effects of material selection on VOC concentrations were evaluated by emissions studies conducted prior to and after the first eight weeks of occupancy and by a comparison of occupied-hour classroom concentrations with the advanced HVAC operational. Slightly lower phenol and 1-methyl-2-pyrrolidinone concentrations in source-modified RCs were attributed to the alternate wall panel. Slightly lower formaldehyde concentrations in these RCs were attributed to the lower-emitting ceiling panels. At one school, teaching materials brought in after the school year began were discovered to be formaldehyde sources. Across SD and RCs in the cooling season, mean concentrations of formaldehyde were 14.1 +/- 6.6 and 30.4 +/- 6.9  $\mu\text{g m}^{-3}$  during advanced and standard HVAC system operation, respectively. Likewise, acetaldehyde mean concentrations were 6.9 +/- 4.7 and 13.7 +/- 3.7  $\mu\text{g m}^{-3}$ , respectively. Similar reductions were observed for toluene and phenol.

Results suggest improved continuous ventilation provided by the advanced HVAC outweighed source reduction as a VOC control measure in these new RCs.

**Shendell, DG, Lee S-M, Apte, MG, DiBartolomeo, DB, Sullivan, DP, Liff, SM, Fisk, WJ, Rainer, LI. "Assessment of Noise Exposures in New Relocatable Classrooms with Standard and Advanced HVAC Systems." Poster presented at the joint annual meeting of the International Society of Exposure Analysis (12<sup>th</sup>) and the International Society of Environmental Epidemiology (14<sup>th</sup>), Vancouver, B.C., Canada, August 11-15, 2002. ABSTRACT published in *Epidemiology*, 13 (4), S223.**

Anecdotal evidence suggests heating, ventilation, and air conditioning (HVAC) systems in modular classrooms are not operated effectively. Teachers are usually in charge of thermal control. Due to inadequate training in HVAC system operation and indoor environmental quality (IEQ) issues, and the relatively loud noise produced by the HVAC system while meeting cooling or heating demands, teachers may avoid using mechanical ventilation. Adequate ventilation is an important link between improved IEQ and energy efficiency for schools. Indoor air quality and physical environmental stresses including noise can adversely impact the health of young children and teachers. During the school year these occupants spend the majority of the 7-8 hour school day inside their classrooms. Therefore, classroom noise levels can be assumed to drive personal school day exposures. As part of a field project of IEQ and energy efficiency, we investigated noise levels in four new relocatable classrooms (RCs). The RCs were equipped with both standard and advanced HVAC systems, alternately operated in a case-crossover study design. Classroom noise data, measured as A-weighted decibels (dB(A)), were collected continuously for the 2001-02 school year with sound level meters (SLM; Extech #407736, Type II, 1.5 dB(A) accuracy, 0.1 dB(A) resolution). A SLM was suspended downward below the ceiling at the center of each 960 ft<sup>2</sup> RC from a specially designed mobile located ~7.0 ft above the floor. The microphone placement and orientation complied with ANSI and IEC specifications; weekly calibration was performed. Reflectance off ceiling tiles, walls, and student desks were negligible. Descriptive statistics were calculated for each classroom for six distinct time periods: start of school day to recess; recess to lunch; the unoccupied lunch period; lunch to end of school day; overnight; and, weekend. Data were stratified by HVAC system in operation and summarized for four periods: fall cooling season; fall-to-winter transitional period; winter heating season; and spring. This study suggests HVAC systems and occupants were the dominant sources of noise exposure for the RCs indoor environment. In the cooling season, at one school, school-day time-weighted average (Leq) values, in dB(A), were 60.0 and 61.0; at the other school, the values in September were 52.2 and 55.7, and in October were 54.3 and 56.0. Examining specific early morning and lunch periods when HVAC systems were on but RCs unoccupied, the advanced system contributed less noise (4-8 dB(A)) than the standard system (10-15 dB(A)). Mean observed classroom noise levels for several time periods, as well as school-day and school morning Leq values, exceeded existing school district, state, and international guidelines of 40-50 dB(A).

**Shendell, D.G., D. DiBartolomeo, W.J. Fisk, A.T. Hodgson, T. Hotchi, S. Min. Lee, D.P. Sullivan, M.G. Apte, and L.I. Rainer. Final methodology for a field study of indoor environmental quality and energy efficiency in new relocatable classrooms in Northern California. 2002. LBNL-51101**

**Shendell, D.G., M.G. Apte, J. Kim, and S. Smorodinsky. "Building effective partnerships to conduct school indoor environmental quality assessments and interventions". Submitted, as "Field Action Report," to: *American Journal Of Public Health*, July 19, 2002. LBNL-50377.**

#### **ABSTRACT**

Public, private, government, and university stakeholders have focused increasing attention on children's environmental health. Priority areas include healthy school environments; susceptibilities of children to environmental factors and associated illness; and, understanding exposure to biological, chemical, and physical agents. As multidisciplinary teams, we have conducted studies and intervention demonstrations in California public schools. A common theme among them was a "partnership," the collaboration between stakeholders from the aforementioned sectors. Federal funding and local bond measures for planning, maintenance, and modernization of school facilities have recently been authorized. Therefore, beneficial "partnerships" should be established to conduct needed IEQ, environmental health, and productivity research, development and demonstration. This field action report describes benefits for stakeholders and five strategies for future effective collaborations.

**Sherman, M.H., Matson, N.E. *Air Tightness of New U.S. Houses: A Preliminary Report*. (2002). LBNL-48671.**

#### **ABSTRACT**

Most dwellings in the United States are ventilated primarily through leaks in the building shell (i.e., infiltration) rather than by whole-house mechanical ventilation systems. Consequently, quantification of envelope air-

tightness is critical to determining how much energy is being lost through infiltration and how much infiltration is contributing toward ventilation requirements.

Envelope air tightness and air leakage can be determined from fan pressurization measurements with a blower door. Tens of thousands of unique fan pressurization measurements have been made of U.S. dwellings over the past decades. LBNL has collected the available data on residential infiltration into its Residential Diagnostics Database, with support from the U.S. Department of Energy. This report documents the envelope air leakage section of the LBNL database, with particular emphasis on new construction.

The work reported here is an update of similar efforts carried out a decade ago, which used available data largely focused on the housing stock, rather than on new construction. The current effort emphasizes shell tightness measurements made on houses soon after they are built. These newer data come from over two dozen datasets, including over 73,000 measurements spread throughout a majority of the U.S. Roughly one-third of the measurements are for houses identified as energy-efficient through participation in a government or utility program. As a result, the characteristics reported here provide a quantitative estimate of the impact that energy-efficiency programs have on envelope tightness in the US, as well as on trends in construction.

**Sherman, M.H., Hodgson, A.T. "Formaldehyde as a Basis for Residential Ventilation Rates" *Journal of Indoor Air* (In Press) (2002). LBNL-49577.**

#### **ABSTRACT**

Traditionally, houses in the U.S. have been ventilated by passive infiltration in combination with active window opening. However in recent years, the construction quality of residential building envelopes has been improved to reduce infiltration, and the use of windows for ventilation also may have decreased due to a number of factors. Thus, there has been increased interest in engineered ventilation systems for residences. The amount of ventilation provided by an engineered system should be set to protect occupants from unhealthy or objectionable exposures to indoor pollutants, while minimizing energy costs for conditioning incoming air. Determining the correct ventilation rate is a complex task, as there are numerous pollutants of potential concern, each having poorly characterized emission rates, and poorly defined acceptable levels of exposure. One ubiquitous pollutant in residences is formaldehyde. The sources of formaldehyde in new houses are reasonably understood, and there is a large body of literature on human health effects. This report examines the use of formaldehyde as a means of determining ventilation rates and uses existing data on emission rates of formaldehyde in new houses to derive recommended levels. Based on current, widely accepted concentration guidelines for formaldehyde, the minimum and guideline ventilation rates for most new houses are 0.28 and 0.5 air changes per hour, respectively.

**Sherman, M.H., Xu, T.T., Abushakra, B., Dickerhoff, D.J., Wang, D.M., Wray, C.P., and Modera, M.P. (2002) *Thermal Distribution System Characteristics and Energy Impacts of Duct Leaks in Light Commercial Buildings*. LBNL-49470. No Abstract Available.**

**Siegel, J.A., Nazaroff, W.W. "Modeling Particle Deposition on HVAC Heat Exchangers". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 1, pp. 521-526. Indoor Air 2002, Santa Cruz, CA. LBNL-49339.**

#### **ABSTRACT**

Fouling of fin-and-tube heat exchangers by particle deposition leads to diminished effectiveness in supplying ventilation and air conditioning. This paper explores mechanisms that cause particle deposition on heat exchanger surfaces. We present a model that accounts for impaction, diffusion, gravitational settling, and turbulence. Simulation results suggest that some submicron particles deposit in the heat exchanger core, but do not cause significant performance impacts. Particles between 1 and 10  $\mu\text{m}$  deposit with probabilities ranging from 1 - 20 % with fin edge impaction representing the dominant mechanism. Particles larger than 10  $\mu\text{m}$  deposit by impaction on refrigerant tubes, gravitational settling on fin corrugations, and mechanisms associated with turbulent airflow. The model results agree reasonably well with experimental data, but the deposition of larger particles at high velocities is underpredicted. Geometric factors, such as discontinuities in the fins, are hypothesized to be responsible for the discrepancy.

**Siegel, J.A., McWilliams, J.A., Walker, I.S. (2002) "Comparison between predicted duct effectiveness from proposed ASHRAE standard 152P and measured field data for residential forced air cooling systems". *ASHRAE Transactions*, Vol. 109, Pt.1. ASHRAE, Atlanta, GA. LBNL-50008.**

## **ABSTRACT**

The proposed ASHRAE Standard 152P "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems" (ASHRAE 2002) has recently completed its second public review. As part of the standard development process, this study compares the forced air distribution system ratings provided by the public review draft of Standard 152P to measured field results. 58 field tests were performed on cooling systems in 11 homes in the summers of 1998 and 1999. Seven of these houses had standard attics with insulation on the attic floor and a well-vented attic space. The other four houses had unvented attics where the insulation is placed directly under the roof deck and the attic space is not deliberately vented. Each house was tested under a range of summer weather conditions at each particular site, and in some cases the amount of duct leakage was intentionally varied. The comparison between 152P predicted efficiencies and the measured results includes evaluation of the effects of weather, duct location, thermal conditions, duct leakage, and system capacity. The results showed that the difference between measured delivery effectiveness and that calculated using proposed Standard 152P is about 5 percentage points if weather data, duct leakage and air handler flow are well known. However, the accuracy of the standard is strongly dependent on having good measurements of duct leakage and system airflow. Given that the uncertainty in the measured delivery effectiveness is typically also about 5 percentage points, the Standard 152P results are acceptably close to the measured data.

**Siegel, Jeffrey, Iain Walker and Max Sherman. "Dirty air conditioners: Energy implications of coil fouling", *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, California; August 18-23, 2002. American Council for an Energy Efficient Economy, Washington, DC. LBNL-49757.**

## **ABSTRACT**

Residential air conditioning is responsible for a substantial amount of peak electrical demand and energy consumption throughout most of the United States. Coil fouling, the deposition of indoor dusts and other particulate matter on evaporator heat exchangers, increases system pressure drop and, correspondingly, decreases system air flow and air conditioner performance. In this paper, we apply experimental and simulation results describing particle deposition on evaporator coils as well as research about indoor particle and dust concentrations to determine coil fouling rates. The results suggest that typical coils foul enough to double evaporator pressure drop in 7 - 11 years, much sooner than the expected 15 - 30 year life time for an evaporator coil. The most important parameters in determining coil fouling times are the efficiency of the filter and indoor particle concentrations, although filter bypass and duct and coil design are important as well. The reduced air flows that result from coil fouling cause typical efficiency and capacity degradations of less than 5 %, however they can be much greater for marginal systems or extreme conditions. These energy issues, as well as possible indoor air quality issues resulting from fouling by biological aerosols, suggest that regular coil cleaning and the elimination of filter bypass should be an important part of residential air conditioning commissioning and maintenance practices.

**Siegel, J.A. and Wray, C.P. (2002) "An Evaluation of Superheat-Based Refrigerant Charge Diagnostics for Residential Cooling Systems", *ASHRAE Transactions*, Vol. 108, Part 2. LBNL-47476.**

## **ABSTRACT**

Although refrigerant charge has an important influence on the performance of residential cooling systems with fixed orifice metering devices, there has been little research to quantify the effects of incorrect charge or design new diagnostics for evaluating charge level. The most common diagnostic for charge level in these systems is the superheat test. In this paper, we examine three superheat technologies/techniques. Two of the diagnostics are appropriate for detecting incorrect charge; one is not. Additionally, measurements at four houses indicate that it is important to measure the condenser air entering temperature with a high degree of accuracy. Measurement of the wet bulb temperature in the return plenum and suction line temperature are equally important, but seemingly easier than measuring the condenser air temperature, as several measurement technologies yielded similar results for these quantities. The importance of refrigerant charge to energy use and capacity of residential cooling systems, the limitations of the superheat test, and the variations in the test method results and interfaces necessitate the development of a standard method or methods to determine refrigerant charge level.

**Singer, B.C., A.T. Hodgson and W.W. Nazaroff. "Effect of sorption on exposures to organic gases from environmental tobacco smoke (ETS), *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 2, pp. 138-143. Indoor Air 2002, Santa Cruz, CA. LBNL-49576.**



#### **ABSTRACT**

The effects of sorption processes on dynamic ETS organic gas concentrations and potential exposures were studied in a carpeted and furnished 50-m<sup>3</sup> room ventilated at 0.6 h<sup>-1</sup>. Ten cigarettes were machine-smoked on six of every seven days over four weeks. Concentrations of ETS-specific tracers and regulated toxic compounds were quantified during daily smoking, post-smoking and background periods. Potential exposures were calculated by period and day. Large sorption effects were observed for the widely used tracers 3-ethenylpyridine and nicotine, and for several toxic compounds including naphthalene and cresol isomers. Short-term adsorption to indoor surfaces reduced concentrations and potential exposures during smoking, while later reemission increased concentrations and exposures hours after smoking ended. Concentrations during nonsmoking periods rose from day to day over the first few weeks, presumably from increased reemission associated with increased sorbed mass concentrations. For sorbing compounds, more than half of daily potential exposures occurred during nonsmoking periods.

**Sippola, M.R., Nazaroff, W.W. (2002) "Modeling Particle Deposition In Ventilation Ducts". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 1, pp. 515-520. Indoor Air 2002, Santa Cruz, CA LBNL-42710.**

#### **ABSTRACT**

This paper describes predictions from two models of fractional particle loss in four typical HVAC duct runs. One model is a state-of-the-art Eulerian formulation; the second is based on empirical fits to experimental particle deposition data collected in a laboratory. The experiments are briefly described and sample results are presented. The Eulerian model only predicts deposition from fully developed turbulence, while the empirical model can be applied to duct bends and developing turbulence as well. The models predict almost no losses for particles smaller than 1 µm and nearly complete loss of particles larger than 40 µm in all duct runs. The empirical model suggests that particle loss in ventilation ducts is dominated by gravitational settling to the floor of horizontal ducts, and by deposition to zones where turbulent flow is undeveloped, such as in bends and in duct sections immediately after bends.

**Sohn, M.D., Reynolds, P., Gadgil, A.J., Sextro, R.G. (2002) "Rapidly Locating Sources And Predicting Contaminant Dispersion In Buildings". (2002) *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 4, pp.211-216. Indoor Air 2002, Santa Cruz, CA. LBNL-49563.**

#### **ABSTRACT**

Contaminant releases in or near a building can lead to significant human exposures unless prompt response measures are taken. However, selecting the proper response depends in part on knowing the source locations, the amounts released, and the dispersion characteristics of the pollutants. We present an approach that estimates this information in real time. It uses Bayesian statistics to interpret measurements from sensors placed in the building yielding best estimates and uncertainties for the release conditions, including the operating state of the building. Because the method is fast, it continuously updates the estimates as measurements stream in from the sensors. We show preliminary results for characterizing a gas release in a three-floor, multi-room building at the Dugway Proving Grounds, Utah, USA.

**Sohn, Michael D.; McKone, T.E.; Blancato, J.N. "Reconstructing Population-scale exposures from dose biomarkers using Bayesian Inference". To be submitted to *Journal of Exposure Analysis & Environmental Epidemiology*. LBNL-50588.**

#### **ABSTRACT**

Physiologically based pharmacokinetic (PBPK) modeling is a well-established toxicological tool designed to transform an exposure into a target tissue dose. The emergence of federal and state programs for environmental health tracking and the availability of exposure monitoring through biomarkers, creates the need to use PBPK models to reconstruct population exposure from urine, blood, and tissue samples. In this paper we lay out and illustrate a plan for examining these questions using an integrated Bayesian statistical framework. The approach provides flexibility for evaluating multiple exposure scenarios and alternative datasets, which will be critical for systematically reconstructing exposures using biomarkers from a large population. We demonstrate the approach by reconstructing population-scale source-to-dose relationships for a population exposed to trichloroethylene (TCE) through inhalation. We used biomarker data from eight adult males who were exposed to TCE vapors in air for 240 minutes in an enclosed chamber. In the application, two groups of individuals had distinctly different TCE concentrations in blood despite being contained in the same experimental chamber. We reconstructed the exposure scenarios for both subgroups with reasonable success because we had an unusually large amount of data - although the reconstruction of one subgroup is different than what is believed to be the

true experimental conditions. We also were unable to predict with high certainty the concentration of TCE in air from any of the datasets. This exercise reveals that reconstruction of exposure conditions from biomarkers using PBPK models requires much care and evaluation to confirm or refute the reliability of the results.

**Thatcher, T.L., Lunden, M.M., Sextro, R.G., Hering, S., Brown, N.J. (2002) "The effect of penetration factor, deposition, and environmental factors on the indoor concentration of pm2.5 sulfate, nitrate, and carbon". (2002) *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 1, pp.846-851. Indoor Air 2002, Santa Cruz, CA. LBNL-50160.**

#### **ABSTRACT**

Indoor exposure to particles of outdoor origin constitutes an important exposure pathway. We conducted an intensive set of indoor particle measurements in an unoccupied house under differing operating conditions. Real-time measurements were conducted both indoors and outdoors, including PM2.5 nitrate, sulfate, and carbon. Because the time-scale of the fluctuations in outdoor particle concentrations and meteorological conditions are often similar to the time constant for building air exchange, a steady state concentration may never be reached. The time-series experimental data were used to determine the effect of changes in air exchange rate and indoor/outdoor temperature and relative humidity differences on indoor particle concentrations. A multivariate regression was performed to investigate the difference between measured indoor concentrations and results from a simple time-dependent physical model. Environmental conditions had a significant effect on indoor concentrations of all three PM2.5 species, but did not explain all of the model variation.

**Thatcher, T.L., D.J. Wilson, E.E. Wood, M.J. Craig, and R.G. Sextro. "Scale modeling of contaminant dispersion indoors". Submitted to *Atmospheric Environment*. LBNL-50248.**

#### **ABSTRACT**

Pollutant dispersion experiments were performed in a water-filled 30:1 scale model of a large room. Theoretical calculations were performed to confirm that the effects from losses of molecular diffusion, small scale eddies, turbulent kinetic energy, and turbulent mass diffusivity were minimal, even without matching Reynolds number between model and full scale. In the experiments, uranine dye was injected continuously from a small point source near the floor of the model. Pollutant concentrations were measured in a plane using laser induced fluorescence techniques. The concentration profiles were measured for three interior configurations for the model: unobstructed, table-like obstructions, and table-like and figure-like obstructions. The presence of objects in the model interior had a significant effect of both the concentration profile and fluctuation intensity in the measurement plane.

**Thatcher, T., M. Lunden, K. Revzan, R. Sextro, and N. Brown. Experimental investigation of the effect of changes in house environment on the indoor concentration of particles of outdoor origin within a residence. LBNL-51002 . Abstract not available.**

**Theaker, I.G. and C.P. Wray. (2002) "Ventilation System Design of Recent Canadian Multi-Unit Residential Buildings", Submitted to *ASHRAE Transactions*, Vol. 106, Part 2, 2002. No Abstract available.**

**Wagner, J., D.P. Sullivan, D. Faulkner, L.A. Gundel, W.J. Fisk, L.E. Alevantis, J.M. Waldman. (2002) "Measurements And Modeling Of Environmental Tobacco Smoke Leakage From A Simulated Smoking Room". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA., Vol. 2, pp. 121-126. Indoor Air 2002, Santa Cruz, CA. LBNL-49785.**

#### **ABSTRACT**

The purpose of this study is to quantify the effect of various design and operating parameters on smoking room performance. Twenty-eight experiments were conducted in a simulated smoking room with a smoking machine and an automatic door opener. Measurements were made of air flows, pressures, temperatures, two particle-phase ETS tracers, two gas-phase ETS tracers, and sulfur hexafluoride. Quantification of leakage flows, the effect of these leaks on smoking room performance and non-smoker exposure, and the relative importance of each leakage mechanism are presented. The results indicate that the first priority for an effective smoking room is to depressurize it with respect to adjoining non-smoking areas. Another important ETS leakage mechanism is the pumping action of the smoking room door. Substituting a sliding door for a standard swing-type door reduced this source of ETS leakage significantly. Measured results correlated well with model predictions ( $R^2 = 0.82-0.99$ ).

**Walker, I.S. and Wray, C.P. (2002) "Evaluation of Flow Capture Techniques for Measuring HVAC Grille Airflows", Submitted to *ASHRAE Transactions*. LBNL-51550.**

**ABSTRACT**

This paper discusses the accuracy of commercially available flow hoods for residential applications. Results of laboratory and field tests indicate these hoods can be inadequate to measure airflows in residential systems, and there can be large measurement discrepancies between different flow hoods. The errors are due to poor calibrations, sensitivity of the hoods to grille airflow non-uniformities, and flow changes from added flow resistance. It is possible to obtain reasonable results using some flow hoods if the field tests are carefully done, the grilles are appropriate, and grille location does not restrict flow hood placement. We also evaluated several simple flow capture techniques for measuring grille airflows that could be adopted by the HVAC industry and homeowners as simple diagnostics. These simple techniques can be as accurate as commercially available devices. Our test results also show that current calibration procedures for flow hoods do not account for field application problems. As a result, agencies such as ASHRAE or ASTM need to develop a new standard for flow hood calibration, along with a new measurement standard to address field use of flow capture techniques.

**Walker, I.S., D.J. Dickerhoff and M.H. Sherman. The Delta Q method of testing the air leakage of ducts. *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, California; August 18-23, 2002, 1:327-338, American Council for an Energy Efficient Economy, Washington, DC LBNL-49749.**

**ABSTRACT**

The DeltaQ test has been developed in order to provide better estimates of forced air system air leakage for use in energy efficiency calculations and for compliance testing of duct systems. The DeltaQ test combines a model of the house and duct system with the results of house pressurization tests with the air handler on and off to determine the duct leakage air flows to outside conditioned space at operating conditions. The key advantage of the DeltaQ test over other methods is that it determines the air leakage flows directly, rather than requiring interpretation of indirect measurements. The results from over 200 field and laboratory tests are presented. The laboratory tests have shown that the DeltaQ repeatability uncertainties are typically 1% or less of system fan flow and that the accuracy of the test is between 1.3% and 2.5% of fan flow (or 13 cfm to 25 cfm (6 to 12 l/s) for this system).

**Webb, A.M., Nazaroff, W.W. and B.C. Singer. "Effect of gaseous ammonia on nicotine sorption". *Proceedings of Indoor Air 2002 Conference*, Monterey, CA, Vol. 3, pp. 512-517. Indoor Air 2002, Santa Cruz, CA. LBNL-50879.**

**ABSTRACT**

Nicotine is a major constituent of environmental tobacco smoke. Sorptive interactions of nicotine with indoor surfaces can substantially alter indoor concentrations. The phenomenon is poorly understood, including whether sorption is fully reversible or partially irreversible. We hypothesize that acid-base chemistry on indoor surfaces might contribute to the apparent irreversibility of nicotine sorption under some circumstances. Specifically, we suggest that nicotine may become protonated on surfaces, markedly reducing its vapor pressure. If so, subsequent exposure of the surface to gaseous ammonia, a common base, could raise the surface pH, causing deprotonation and desorption of nicotine from surfaces. A series of experiments was conducted to explore the effect of ammonia on nicotine sorption to and reemission from surfaces. Our results indicate that, under some conditions, exposure to gaseous ammonia can substantially increase the rate of desorption of previously sorbed nicotine from common indoor surface materials.

**Wray, Craig P. (2002) "Suite Ventilation Characteristics of Current Canadian Mid-and High-Rise Residential Buildings". 106 (Part 2) 2002. LBNL-43254.**

**ABSTRACT**

This paper characterizes ventilation in residential suites located in ten buildings in major metropolitan areas of Canada. All buildings were between six and thirty-two stories tall and were built between 1990 and 1995.

1. The key findings from field performance tests of these buildings were:
2. Corridor supply airflows usually did not meet design flows.
3. Makeup air paths for suite exhaust were not properly designed.
4. Suite access door leakage was highly variable and usually did not meet smoke control requirements.
5. Airflow from the corridor through the suite access door leakage appeared to be the primary ventilation air supply for suites.

6. Suites were usually well-ventilated, but some were marginally- or under-ventilated.
7. Poor pressure control often allowed transfer air from one suite to another. Inter-suite transfer air fractions ranged from 0 to 45%, with an average of 19%.

In summary, this work showed suite ventilation can be highly influenced by corridor supply flows, by the treatment of corridor access doors, and by transfer airflows. As a result, suite ventilation at any given time in current mid- and high-rise residential buildings is very difficult to predict.

To ensure suite ventilation performs as intended under all operating conditions, the building industry needs to address the identified problems through improved ventilation design, operation, and maintenance practices.

**Wray, Craig P., Iain S. Walker and Max H. Sherman. "Accuracy of flow hoods in residential applications". *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, California; August 18-23, 2002, 1:339-350, American Council for an Energy Efficient Economy, Washington, DC LBNL-49697.**

#### **ABSTRACT**

To assess whether houses can meet performance expectations, the new practice of residential commissioning will likely use flow hoods to measure supply and return grille airflows in HVAC systems. Depending on hood accuracy, these measurements can be used to determine if individual rooms receive adequate airflow for heating and cooling, to determine flow imbalances between different building spaces, to estimate total air handler flow and supply/return imbalances, and to assess duct air leakage. This paper discusses these flow hood applications and the accuracy requirements in each case. Laboratory tests of several residential flow hoods showed that these hoods can be inadequate to measure flows in residential systems. Potential errors are about 20% to 30% of measured flow, due to poor calibrations, sensitivity to grille flow non-uniformities, and flow changes from added flow resistance. Active flow hoods equipped with measurement devices that are insensitive to grille airflow patterns have an order of magnitude less error, and are more reliable and consistent in most cases. Our tests also show that current calibration procedures for flow hoods do not account for field application problems. As a result, a new standard for flow hood calibration needs to be developed, along with a new measurement standard to address field use of flow hoods. Lastly, field evaluation of a selection of flow hoods showed that it is possible to obtain reasonable results using some flow hoods if the field tests are carefully done, the grilles are appropriate, and grille location does not restrict flow hood placement.

**Wray, C.P., Walker, I.S., Siegel, J.A., and Sherman, M.H. (2002) *Practical Diagnostics for Evaluating Residential Commissioning Metrics*. LBNL-45959.**

#### **ABSTRACT**

In this report, we describe what residential commissioning is, its characteristic elements, and how one might structure its process. Our intent in this discussion is to formulate and clarify these issues, but is largely preliminary because such a practice does not yet exist. Subsequent sections of the report describe metrics one can use in residential commissioning, along with the consolidated set of 24 practical diagnostics that the building industry can use now to evaluate them. Our discussion in the main body of this report is limited to existing diagnostics in areas of particular concern with significant interactions: envelope and HVAC systems. These areas include insulation quality, windows, airtightness, envelope moisture, fan and duct system airflows, duct leakage, cooling equipment charge, and combustion appliance backdrafting with spillage.

Where possible, we also discuss the accuracy and usability of diagnostics, based on recent laboratory work and field studies by LBNL staff and others in more than 100 houses. These studies concentrate on evaluating diagnostics in the following four areas: the DeltaQ duct leakage test, air-handler airflow tests, supply and return grille airflow tests, and refrigerant charge tests. In addition, where possible, we identify the costs to purchase diagnostic equipment and the amount of time required to conduct the diagnostics.

**Xu, T.T., Carrie, F.R., Dickerhoff, D.J., Fisk, W.J., McWilliams, J., Wang, D., Modera, M.P. (2002) "Performance of thermal distribution systems in large commercial buildings". *Energy and Buildings* 34:215-226. LBNL-44331.**

#### **ABSTRACT**

This paper presents major findings of a field study on the performance of five thermal distribution systems in four large commercial buildings. The five systems studied are typical single-duct or dual-duct constant air volume (CAV) systems and variable air volume (VAV) systems, each of which serves an office building or a retail building with floor area over 2,000 m<sup>2</sup>. The air leakage from ducts are reported in terms of effective

leakage area (ELA) at 25 Pa reference pressure, the ASHRAE-defined duct leakage class, and air leakage ratios. The specific ELAs ranged from 0.7 to 12.9 cm<sup>2</sup> per m<sup>2</sup> of duct surface area, and from 0.1 to 7.7 cm<sup>2</sup> per square meter of floor area served. The leakage classes ranged from 34 to 757 for the five systems and systems sections tested. The air leakage ratios are estimated to be up to one-third of the fan-supplied airflow in the constant-air-volume systems. The specific ELAs and leakage classes indicate that air leakage in large commercial duct systems varies significantly from system to system, and from system section to system section even within the same thermal distribution system. The duct systems measured are much leakier than the ductwork specified as "unsealed ducts" by ASHRAE. Energy losses from supply ducts by conduction (including convection and radiation) are found to be significant, on the scale similar to the losses induced by air leakage in the duct systems. The energy losses induced by leakage and conduction suggest that there are significant energy-savings potentials from duct-sealing and insulation practice in large commercial buildings.

**Xu, T., M. Sherman, B. Abushakra, C. Wray, D. Dickerhoff, D. Wang, and M. Modera. Characterizations of thermal distribution systems and energy impacts of duct leaks in light commercial buildings. LBNL-49470. No Abstract available.**

**Zhao, D., Little, J.C., Hodgson, A.T. (2002) "Modeling the Reversible Sink Effect in Response to Transient Contaminant Sources". Indoor Air 12: 184-190. LBNL-47095.**

#### **ABSTRACT**

A physically based diffusion model is used to evaluate the sink effect of diffusion-controlled indoor materials and to predict the transient contaminant concentration in indoor air in response to several time-varying contaminant sources. For simplicity, it is assumed that the predominant indoor material is a homogeneous slab, initially free of contaminant, and that the air within the room is well mixed. The model enables transient volatile organic compound (VOC) concentrations to be predicted based on the material/air partition coefficient (K) and the material-phase diffusion coefficient (D) of the sink. Model predictions are made for four scenarios, each mimicking a realistic situation in a building. Styrene, phenol, and naphthalene are used as representative VOCs. A styrene butadiene rubber (SBR) backed carpet, vinyl flooring (VF), and a polyurethane foam (PUF) carpet cushion are considered as typical indoor sinks. In scenarios involving a sinusoidal VOC input and a double exponential decaying input, the model predicts that the sink has a modest impact for SBR/styrene, but that the effect increases for VF/phenol and PUF/naphthalene. In contrast, for an episodic chemical spill, SBR is predicted to reduce the peak styrene concentration considerably. A parametric study reveals that for systems involving a high equilibrium factor (K), the kinetic factor (D) will govern the shape of the resulting gas-phase concentration profile. On the other hand, for systems with a relaxed mass transfer resistance, K will dominate the profile.

### **2001 Publications without Abstracts**

- Apte, M.G., Fisk, W.J., Hodgson, A.T., Russell, M., Shendell, D.G. (2001) "California Demonstration Energy Efficiency-Indoor Environmental Quality Project: Predicted Relocatable Classroom Indoor Air Quality due to Low-Emitting Interior Materials and Enhanced Ventilation." In: *Proceedings of the 11<sup>th</sup> Annual Meeting of the International Society of Exposure Analysis*, Charleston, SC, November 4-8, 2001 (Abstract).
- Apte, M.G., Delp, W.W., Diamond, R.C., Hodgson, A.T., Kumar, S., Shendell, D.G., Sullivan, D.P., Fisk, W.J. (2001) *Report on HVAC Option Selections for a Relocatable Classroom Energy and Indoor Environmental Quality Field Study*. LBNL-49026.
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- Bennett, D.H., T.E. McKone, and W.E. Kastenberg, "Characteristic time, characteristic travel distance, and population based dose in a multimedia environment: A case study," in D. Paustenbach, (Ed.), *Human & Ecological Risk Assessment: Theory and Practice* (John Wiley and Sons, New York, 2001). LBNL-45815.
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- Cox, S.S., Hodgson, A.T., Little, J.C. (2001) "Measuring Concentrations of Volatile Organic Compounds in Vinyl Flooring". *Air & Waste Manage. Assoc.* 51:174-185 2001. LBNL-47086.
- Cox, S.S., Hodgson, A.T., Little, J.C. (2001) *Predicting the Emission Rate of Volatile Organic Compounds from Vinyl Flooring*. LBNL-47094.

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- Klepeis, Neil E., William C. Nelson, Wayne R. Ott, John P. Robinson, Andy M. Tsang, Paul Switzer, Joseph V. Behar, Stephen C. Hern, and William H. Engelmann. "The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants". *Journal of Exposure Analysis and Environmental Epidemiology*, v.11, no.3 (May-Jun. 2001): pp.231-252. LBNL-47713
- Liu, D.L., Nazaroff, W.W. (2001) "Modeling pollutant penetration across building envelopes". *Atmospheric Environment*, **35**(26):4451-4462. LBNL-47785.
- Lunden, M.M., Thatcher, T.L., Littlejohn, D., Fischer, M.L., Kirchstetter, T.W., Brown, N.J., Hering, S., and Stolzenburg, M. (2001) *Building a predictive model of indoor concentrations of outdoor PM-2.5 in homes*. LBNL-48929.

**MacLeod, M., D.G. Woodfine, D. Mackay, T.E. McKone, D.H. Bennett, and R.L. Maddalena. "BETR North America: A regionally segmented multimedia contaminant fate model for North America". *Environmental Science & Pollution Research*, v.8; no.3; pp.156-163; 2001. LBNL-50571.**

#### **ABSTRACT**

We present the Berkeley-Trent North American contaminant fate model (BETR North America), a regionally segmented multimedia contaminant fate model based on the fugacity concept. The model is built on a framework that links contaminant fate models of individual regions, and is generally applicable to large, spatially heterogeneous areas. The North American environment is modeled as 24 ecological regions, within each region contaminant fate is described using a 7 compartment multimedia fugacity model including a vertically segmented atmosphere, freshwater, freshwater sediment, soil, coastal water and vegetation compartments. Inter-regional transport of contaminants in the atmosphere, freshwater and coastal water is described using a database of hydrological and meteorological data compiled with Geographical Information Systems (GIS) techniques. Steady-state and dynamic solutions to the 168 mass balance equations that make up the linked model for North America are discussed, and an illustrative case study of toxaphene transport from the southern United States to the Great Lakes Basin is presented. Regionally segmented models such as BETR North America can provide a critical link between evaluative models of long-range transport potential and contaminant concentrations observed in remote regions. The continent-scale mass balance calculated by the model provides a sound basis for evaluating long-range transport potential of organic pollutants, and formulation of continent scale management and regulatory strategies for chemicals.

- McKone, T.E. and E.G. Hertwich, "The Human Toxicity Potential and a Strategy for Evaluating Model Performance in Life-Cycle Impact Assessment," *International Journal of Life-Cycle Assessment*, 6(2):106-109, 2001. LBNL-48254.
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Assessments Through Public-Private-Government Partnerships, Examples from CA and TX.” In: *Proceedings of the 11<sup>th</sup> annual meeting of the International Society for Exposure Analysis*, Charleston, SC, November 4-8, 2001, pp. 148 (Abstract).

Sherman, M.H., Walker, I.S. (2001) “Heat Recovery in Building Envelopes”. In: *Proceedings of Thermal Performance of Exterior Envelopes of Buildings VIII*. ASHRAE, Atlanta, GA In Press. LBNL-47329.

Siegel, J., Wray, C.P., Eng, P. (2001) *An Evaluation of Superheat-Based Refrigerant Charge Diagnostics for Residential Cooling Systems*. LBNL-47476.

**Siegel, Jeffrey. (2001) *Fouling of HVAC fin and tube heat exchangers*. LBNL-47668.**

#### **ABSTRACT**

Fin and tube heat exchangers are used widely in residential, commercial and industrial HVAC applications. Invariably, indoor and outdoor air contaminants foul these heat exchangers. This fouling can cause decreased capacity and efficiency of the HVAC equipment as well as indoor air quality problems related to microbiological growth. This paper describes laboratory studies to investigate the mechanisms that cause fouling. The laboratory experiments involve subjecting a 4.7 fins/cm (12 fins/inch) fin and tube heat exchanger to an air stream that contains monodisperse particles. Air velocities ranging from 1.5 - 5.2 m/s (295 ft/min - 1024 ft/min) and particle sizes from 1 – 8.6  $\mu\text{m}$  are used. The measured fraction of particles that deposit as well as information about the location of the deposited material indicate that particles greater than about 1  $\mu\text{m}$  contribute to fouling. These experimental results are used to validate a model that describes the relative importance of several deposition mechanisms including impaction, Brownian diffusion, turbophoresis and gravitational settling. The analysis is extended to apply to different fin spacings and particle sizes typical of those found in indoor air.

**Siegel, J.A., Walker, I.S. (2001) *Deposition of biological aerosols on HVAC heat exchangers*. LBNL-47669.**

#### **ABSTRACT**

Many biologically active materials are transported as bioaerosols 1-10  $\mu\text{m}$  in diameter. These particles can deposit on cooling and heating coils and lead to serious indoor air quality problems. This paper investigates several of the mechanisms that lead to aerosol deposition on fin and tube heat exchangers. A model has been developed that incorporates the effects of several deposition mechanisms, including impaction, Brownian and turbulent diffusion, turbophoresis, thermophoresis, diffusiophoresis, and gravitational settling. The model is applied to a typical range of air velocities that are found in commercial and residential HVAC systems 1 - 6 m/s (200 - 1200 ft/min), particle diameters from 1 - 8  $\mu\text{m}$ , and fin spacings from 3.2 - 7.9 fins/cm (8 - 16 fins/inch or FPI). The results from the model are compared to results from an experimental apparatus that directly measures deposition on a 4.7 fins/cm (12 FPI) coil. The model agrees reasonably well with this measured data and suggests that cooling coils are an important sink for biological aerosols and consequently a potential source of indoor air quality problems.

Sohn, M.D., Reynolds, P., Singh, N., Gadgil, A.J. (2001) *Rapidly locating and characterizing pollutants in buildings: An application of Bayesian data analysis*. LBNL-47588.

Sohn, Michael D., Thomas E. McKone, Mark L. Rigas, Jerry N. Blancato, and Frederick W. Power. Reconstructing exposure scenarios using dose biomarkers: An application of Bayesian uncertainty analysis. LBNL-51256 Abs.

Tenwolde, A., Walker, I.S. (2001). "Interior Moisture Design Loads for Residences ". In: *Proceedings of Thermal Performance of Exterior Envelopes of Buildings VIII*. ASHRAE, Atlanta, GA. In Press.

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Thatcher, T.L., T.E. McKone, W.J. Fisk, M.D. Sohn, W.W. Delp, W.J. Riley, and R.G. Sextro, (2001) *Factors Affecting the Concentration of Outdoor Particles Indoors (COPI): Identification of Data Needs and Existing Data*. LBNL-49321.

**Walker, I.S., Siegel, J.A, Degenetals, G. (2001) “Simulation of Residential HVAC System Performance”. In: *Proceedings of ESIM2001 Conference*, pp. 43-50. CANMET Energy Technology Centre/Natural Resources Canada, Ottawa, Ontario, Canada. LBNL-47622.**

#### **ABSTRACT**

In many parts of North America residential HVAC systems are installed outside conditioned space. This leads to significant energy losses and poor occupant comfort due to conduction and air leakage losses from the air distribution

ducts. In addition, cooling equipment performance is sensitive to air flow and refrigerant charge that have been found to be far from manufacturers specifications in most systems. The simulation techniques discussed in this paper were developed in an effort to provide guidance on the savings potentials and comfort gains that can be achieved by improving ducts (sealing air leaks) and equipment (correct air-flow and refrigerant charge). The simulations include the complex air flow and thermal interactions between duct systems, their surroundings and the conditioned space. They also include cooling equipment response to air flow and refrigerant charge effects. Another key aspect of the simulations is that they are dynamic - which accounts for cyclic losses from the HVAC system and the effect of cycle length on energy and comfort performance.

**Walker, I.S. (2001) *Sensitivity of forced air distribution system efficiency to climate, duct location, air leakage and insulation*. LBNL 43371.**

#### **ABSTRACT**

This study was performed in order to find suitable efficiency and leakage specifications for Energy Star duct systems and provide recommendations on duct insulation specifications. This analysis looks at a typical house, with a selection of duct locations, climates, duct insulation (R-value), and duct leakage. A set of calculations were performed with reduced capacity and airflow to look at the effect of variable capacity systems. This was done to address concerns regarding the increased efficiency of multi-capacity equipment due to good part load performance and how these efficiency gains may be offset by increased duct losses. The duct system efficiencies were calculated using the procedures in proposed ASHRAE Standard 152P "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems" (ASHRAE 1999). This proposed ASHRAE Standard can be used to calculate duct efficiency for both design and seasonal weather conditions. In this report, the seasonal efficiencies are used for most of the analysis because they are the most appropriate for estimating energy consumption in buildings. The effects at peak conditions are examined for changing duct insulation in order to provide preliminary estimates of the potential responses to time of use pricing.

The study was performed in two parts. The first part focused on duct leakage and the second part on duct insulation. The HVAC systems in the two parts share many attributes, however, they differ in detail and so are treated separately here. All the calculation results are summarized in tables in the Appendix, and specific results are given in the text.

**Walker, I.S., Sherman, M.H., Wempen, J., Wang, D., McWilliams, J.A., Dickerhoff, D.J. (2001) *Development of a New Duct leakage Test: Delta Q*. LBNL-47308.**

#### **ABSTRACT**

Duct leakage is a key factor in determining energy losses from forced air heating and cooling systems. Several studies (Francisco and Palmiter 1997 and 1999, Andrews et al. 1998, and Siegel et al. 2001) have shown that the duct system efficiency cannot be reliably determined without good estimates of duct leakage. Specifically, for energy calculations, it is the duct leakage air flow to outside at operating conditions that is required. Existing test methods either precisely measure the size of leaks (but not the flow through them at operating conditions), or measure these flows with insufficient accuracy. The DeltaQ duct leakage test method was developed to provide improved estimates of duct leakage during system operation.

In this study we developed the analytical calculation methods and the test procedures used in the DeltaQ test. As part of the development process, we have estimated uncertainties in the test method (both analytically and based on field data) and designed automated test procedures to increase accuracy and reduce the contributions of operator errors in performing field tests. In addition, the test has been evaluated in over 100 houses by several research teams to show that it can be used in a wide range of houses and to aid in finding limits or problems in field applications. The test procedure is currently being considered by ASTM as an update of an existing duct leakage standard.

**Walker, I.S., Wray, C.P., Dickerhoff, D.J., Sherman, M.H. (2001) *Evaluation of flow hood measurements for residential register flows*. LBNL-47382.**

#### **ABSTRACT**

Flow measurement at residential registers using flow hoods is becoming more common. These measurements are used to determine if the HVAC system is providing adequate comfort, appropriate flow over heat exchangers and in



estimates of system energy losses. These HVAC system performance metrics are determined by using register measurements to find out if individual rooms are getting the correct airflow, and in estimates of total air handler flow and duct air leakage. The work discussed in this paper shows that commercially available flow hoods are poor at measuring flows in residential systems. There is also evidence in this and other studies that flow hoods can have significant errors even when used on the non-residential systems they were originally developed for. The measurement uncertainties arise from poor calibrations and the sensitivity of exiting flow hoods to non-uniformity of flows entering the device. The errors are usually large – on the order of 20% of measured flow, which is unacceptably high for most applications. Active flow hoods that have flow measurement devices that are insensitive to the entering air flow pattern were found to be clearly superior to commercially available flow hoods. In addition, it is clear that current calibration procedures for flow hoods may not take into account any field application problems and a new flow hood measurement standard should be developed to address this issue.

**Wray, C.P., Sherman, M.H. (2001) “Residential Commissioning to Assess Envelope and HVAC System Performance” (2001) In: *Proceedings of Performance of Exterior Envelopes of Whole Buildings VIII Conference*, Clearwater Beach, FL., December 2001. LBNL-47412.**

#### **ABSTRACT**

Residential commissioning is a new procedure to ensure that a house can perform optimally or at least meet basic safety, health, comfort, and energy intents. Many procedural elements, such as visual inspection and functional performance diagnostics, already exist in a fragmented environment. Most can be integrated into new industry guidelines for testing and tuning system performance in new and existing houses.

This paper describes a consolidated set of practical diagnostics that can be used now to commission envelope and HVAC system performance. Where possible, we discuss the accuracy and usability of available diagnostics, based on recent laboratory work and field studies. We also describe areas in need of research and development, such as practical field diagnostics for envelope thermal conductance and combustion safety.

**Wray, C.P., Walker, I.S., Siegel, J.A., M.H. Sherman. (2001) *Practical Diagnostics for Evaluating Residential Commissioning Metrics*. LBNL-45959.**

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#### ABSTRACT

Residential thermal distribution systems have significant energy and comfort implications due to losses from the distribution system in the form of leakage and conduction and poor distribution from room-to-room within the house. Also, poor mechanical equipment performance, and the interactions between the distribution system and the equipment act to further reduce system capacity and thermal comfort. An example of duct system and equipment interaction is the that airflow over the indoor coils changes the efficiency, capacity and humidity removal of the system resulting in comfort, energy consumption and efficiency changes. To determine if there are any differences in the interactions depending on whether or not the equipment is ENERGYSTAR rated, two houses were tested with standard (SEER10) air conditioners and then retrofitted with ENERGYSTAR (SEER 13) equipment. In addition, the effect of duct leakage was examined by adding leaks to the systems under test. The original plan had been to seal the duct systems, but they were found to be not very leaky. Leakage was added in order to show the effect of reduced leakage. Four additional houses were tested as part of a companion study (Walker et al. (1999)) that did not have equipment changes. Selected measurement results from these houses are presented where appropriate.

This report is in two main parts. The first part discusses the field measurement techniques and results. The second part examines efforts to model distribution system performance using a sophisticated computer simulation program called REGCAP. REGCAP has been developed to specifically include the interactions of duct systems with their surroundings (In this study the duct surroundings are attic spaces). Lastly, a brief summary of related thermal distribution system research is included at the end of the report.

**Wray, C.P., Matson, N.E., and Sherman, M.H. (2000) "Selecting Whole-House Ventilation Strategies to Meet Proposed ASHRAE 62.2: Energy Cost Considerations", *ASHRAE Transactions*, Vol. 106, Part 2, pp. 681-691. LBNL-44479.**

#### ABSTRACT

ASHRAE Standard 62.2P is being proposed to address residential ventilation issues. As housing, especially new housing, gets more airtight and better insulated, it has become clear that many homes are under-ventilated. The Standard contains requirements that provide minimum ventilation rates and source control measures necessary for acceptable indoor air quality. This paper uses previously reported analytical techniques to compare the energy costs of various ventilation strategies for a wide variety of climates and housing types. For new construction, we conclude that mechanical ventilation is needed. In new houses with gas heating, the cheapest whole-house system is a central exhaust fan. The marginal energy costs to provide such ventilation are on the order of 50¢ per day. However, other systems can be more appropriate when depressurization, filtration, moisture, and more expensive heating fuels are considered. For most of the existing housing stock, we conclude that infiltration provides adequate ventilation.

Wray, C.P. and Sherman, M.H. (2000) *Residential Commissioning to Assess Envelope and HVAC System Performance*. LBNL-47412.

Wray, C.P., Piette, M.A., Sherman, M.H., Levinson, R.M., Matson, N.E., Driscoll, D.A., McWilliams, J.A., Xu, T.T., Delp, W.W. (2000) *Residential Commissioning: A Review of Related Literature*. LBNL-44535.

## ABSTRACT

The literature review reported here is the first step in a larger 30 month-long project that will lay the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. The intent of the review is to facilitate access to existing literature related to residential commissioning. Emphasis is placed on reviewing documents published over the past 20 years, which represents the period of time over which building commissioning and closely related issues have been actively reported.

This report discusses the status of commercial building commissioning and compares it with residential commissioning. Based on an extensive review of 469 readily available documents, it summarizes existing metrics, diagnostics, and norms for all building types that are relevant for evaluating, tuning, and retrofitting various aspects of new and existing houses. The relevant areas of concern for California houses are: Building Envelope, Cooling Equipment and Heat Pumps, Air Distribution Systems, Indoor Air Quality, Combustion Appliances, Controls, and Other Electrical Appliances.

There is a substantial amount of useful information in the literature about metrics, diagnostics, and norms that are relevant to residential commissioning. However, there are also some significant gaps. This report concludes by highlighting gaps in existing knowledge that require further research and development. Areas in particular need of work include: metrics, diagnostics, and norms for thermal mass and moisture-damage susceptibility; diagnostics for steady-state capacity and efficiency, as well as refrigerant charge level, for cooling equipment and heat pumps; diagnostics and norms for ventilation effectiveness and efficiency; diagnostics to evaluate the potential for backdrafting and combustion gas spillage; and metrics, diagnostics, and norms for controls and other electrical appliances.

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Apte, M.G., Gundel, L.A., Singer, B.C., Sullivan, D.P., Sextro, R.G. (1999) “Indoor Transport of ETS Particles And Tracers”. In: *Proceedings of Indoor Air 99* , Vol. 2, pp 965-970, Construction Research Communications Inc., London. LBNL-43841.

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Daisey, J. (1999) “Indoor Air Quality, Ventilation and Health Symptoms in Schools: An Analysis of Existing Information” In: *Proceedings of Indoor Air 99*, Vol. 2, pp 1-6, Construction Research Communications Inc., London.

Diamond, R.C., Feustel, H.E., Matson, N. (1999) *A Guide to Energy Efficient Ventilation in Apartment Buildings*. US Department of Energy (DOE/EE-0196). LBNL-43641.

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**Walker, I.S. (1999) "Distribution System Leakage Impacts on Apartment Building Ventilation Rates", *ASHRAE Transactions*, 105(1): 943-950.**

#### **ABSTRACT**

Forced air distribution systems in residential buildings are often located outside conditioned space, for example in attics, crawlspaces, garages and basements. Leaks from the ducts to these unconditioned spaces or outside can change flows through the registers and change the ventilation rates of the conditioned spaces. In this study, duct leakage flows were measured in several low-rise apartment buildings. The leakage flow measurements and other data about the apartments were used to develop a prototype apartment building. The multizone airflow model COMIS was then used on this prototype building to determine internal flows within the building, air flows through the building envelope and the impacts of the duct leakage on the ventilation rates. The effects of sealing the duct leaks were also examined in order to determine changes in infiltration rates resulting from duct retrofits. The simulation results showed that for the prototype tested here, the excess return leakage tended to decrease envelope infiltration flows by about 20% but the total infiltration load including return duct leaks more than doubled during system operation.

**Walker, I.S., Sherman, M.H., Siegel, J.A. (1999) *Distribution effectiveness and impacts on equipment sizing for residential thermal distribution systems*. LBNL-43724.**

#### **Introduction**

Previous studies (including earlier phases of this research project) have shown that losses from residential thermal distribution systems have significant energy and comfort implications. This study looks at the potential for improvement of thermal distribution systems and the possibility of reducing equipment size as a result. These distribution system and equipment interactions were examined through field testing and computer simulation. In addition, this report outlines our efforts to transfer the results of this research to the marketplace so as to reduce energy losses and improve thermal comfort. This study describes the results of efforts made during the Transitional Phase of this Residential Thermal Distribution Systems research. Results of earlier Phases were described in Walker et al. (1997 and 1998).

**Wray, C.P. (1999) "Suite Ventilation Characteristics of Current Canadian Mid- and High-Rise Residential Buildings", Submitted to *ASHRAE Transactions*. LBNL-43254.**

#### **ABSTRACT**

This paper characterizes ventilation in residential suites located in ten buildings in major metropolitan areas of Canada. All buildings were between six and thirty-two stories tall and were built between 1990 and 1995.

The key findings from field performance tests of these buildings were:

1. Corridor supply airflows usually did not meet design flows.
2. Makeup air paths for suite exhaust were not properly designed.
3. Suite access door leakage was highly variable and usually did not meet smoke control requirements.
4. Airflow from the corridor through the suite access door leakage appeared to be the primary ventilation air supply for suites.
5. Suites were usually well-ventilated, but some were marginally- or under-ventilated.
6. Poor pressure control often allowed transfer air from one suite to another. Inter-suite transfer air fractions ranged from 0 to 45%, with an average of 19%.

In summary, this work showed suite ventilation can be highly influenced by corridor supply flows, by the treatment of corridor access doors, and by transfer airflows. As a result, suite ventilation at any given time in current mid- and high-rise residential buildings is very difficult to predict.

To ensure suite ventilation performs as intended under all operating conditions, the building industry needs to address the identified problems through improved ventilation design, operation, and maintenance practices.

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**Walker, I.S., Modera, M.P. (1998) "Field Measurements of the Interactions between Furnaces and Forced Air Distribution Systems", *ASHRAE Trans.*, **104**(1B): 1805-1816. LBNL-40587.**

#### **ABSTRACT**

Measurements on three gas and two electric furnaces have been made to examine the field performance of these furnaces and their interactions with their forced-air distribution systems. The distribution systems were retrofitted as part of this study and the impact of retrofitting on furnace performance is discussed. In addition to field measurements, this paper will discuss how forced-air furnace systems are treated in proposed ASHRAE Standard 152P, and applies the resulting equations to the systems tested in the field. The distribution system calculations in Standard 152P are compared to the current methods employed in the "Furnaces" chapter of ASHRAE's *HVAC Systems and Equipment Handbook*, showing how the distribution system efficiencies calculated using Standard 152P can be incorporated into the handbook.

**Walker, I., Sherman, M., Modera, M., Siegel, J. (1998) *Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems*. LBNL-41118.**

#### **Introduction**

This field study concentrated on measurement of duct leakage to outside the conditioned space because this is most useful in energy calculations, e.g., proposed ASHRAE Standard 152P (ASHRAE 1997). For room by room load/comfort requirements, the total duct leakage (including leaks to conditioned space) is more appropriate, particularly for additional comfort considerations. The objective of this field study is to help to identify major sources of uncertainty and to quantify the trade-offs between different test methods. The identification of the areas requiring significant improvement will aid in future development of duct leakage test methods. For example, during the course of this study a new method for correcting house pressure tests to account for the presence of duct leakage in measured envelope leakage was developed.

Each of the measurement techniques investigated has resulted from a different set of priorities and hence compromises. Thus each one of them is measuring a different physical quantity, although they all report the same parameter - duct leakage to outside at operating conditions. Given that real houses do not meet all of the simplifying assumptions that must be made to achieve similarity, the same numbers from each test method are not expected. Potentially these differences can be quite large and one of the benefits of field measurement is that the differences in the measurements helps put a realistic bound on how different some of these leakage diagnostics may be.

To evaluate current duct leakage diagnostic methods, field tests were performed in 17 houses. The field



tests were divided into two parts. The first part was performed in occupied S.F. Bay Area houses. The second part was performed in new unoccupied houses (some with unfinished interiors) in Irvine, CA. In the Bay Area, nine houses were tested using four diagnostic techniques.

**Walker, I.S., Wilson, D.J. (1998) "Field Validation of Algebraic Equations for Stack and Wind Driven Air Infiltration Calculations", *HVAC&R Research*, 4: 119-139. LBNL-42361.**

#### **ABSTRACT**

Explicit algebraic equations for calculation of wind and stack driven ventilation were developed by parametrically matching exact solutions to the flow equations for building envelopes. These separate wind and stack effect flow calculation procedures were incorporated in a simple natural ventilation model, AIM-2, with empirical functions for superposition of wind and stack effect and for estimating wind shelter. The major improvements over previous simplified ventilation calculations are: a power law pressure-flow relationship is used to develop the flow equations from first principles, the furnace or fireplace flue is included as a separate leakage site and the model differentiates between houses with basements (or slab-on-grade) and crawlspaces. Over 3400 hours of measured ventilation rates from the test houses at the Alberta Home Heating Research Facility were used to validate the predictions of ventilation rates and to compare the AIM-2 predictions to those of other ventilation models. The AIM-2 model had bias and scatter errors of less than 15% for wind-dominated ventilation, and less than 7% for buoyancy ("stack-effect") dominated cases.

**Walker, I.S., Wilson, D.J., Sherman, M.H. (1998) "A Comparison of the Power Law to Quadratic Formulations for Air Infiltration Calculations", *Energy and Buildings*, 27(3): 293-299. LBNL-41447.**

#### **Synopsis**

Although the power law has been broadly accepted in measurement and air infiltration standards, and in many air infiltration calculation methods, the assumption that the power law is true over the range of pressures that a building envelope experiences has not been well documented. In this paper, we examine the validity of the power law through theoretical analysis, laboratory measurements of crack flow and detailed field tests of building envelopes. The results of the theoretical considerations, and field and laboratory measurements indicate that the power law is valid for low pressure building envelope leakage.

**Walker, I., Siegel, J., Brown, K., Sherman, M. (1998) "Saving Tons at the Register". In: *Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings*, Vol. 1, pp 367-383, American Council for an Energy Efficient Economy, Washington, D.C. LBNL-41957.**

#### **ABSTRACT**

Duct losses have a significant effect on the efficiency of delivering space cooling to U.S. homes. This effect is especially dramatic during peak demand periods where half of the cooling equipment's output can be wasted. Improving the efficiency of a duct system can save energy, but can also allow for downsizing of cooling equipment without sacrificing comfort conditions. Comfort, and hence occupant acceptability, is determined not only by steady-state temperatures, but by how long it takes to *pull down* the temperature during cooling start-up, such as when the occupants come home on a hot summer afternoon. Thus the delivered tons of cooling at the register during start-up conditions are critical to customer acceptance of equipment downsizing strategies. We have developed a simulation technique which takes into account such things as weather, heat-transfer (including hot attic conditions), airflow, duct tightness, duct location and insulation, and cooling equipment performance to determine the net tons of cooling delivered to occupied space. Capacity at the register has been developed as an improvement over equipment tonnage as a system sizing measure. We use this concept to demonstrate that improved ducts and better system installation is as important as equipment size, with analysis of pull-down capability as a proxy for comfort. The simulations indicate that an improved system installation including tight ducts can eliminate the need for almost a ton of rated equipment capacity in a typical new 2,000 square foot house in Sacramento, California. Our results have also shown that a good duct system can reduce capacity requirements and still provide equivalent cooling at start-up and at peak conditions.

**Walker, I.S., (1998) "Technical Background for Default Values used for Forced Air Systems in Proposed ASHRAE Standard 152P", *ASHRAE Trans.*, 104(1B): 1360-1375. LBNL-40588**

## ABSTRACT

ASHRAE Standard 152P (Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems) includes default values for many of the input parameters required to calculate delivery system efficiencies. These default values have several sources: measured field data in houses, laboratory testing, simple heat transfer analyses, etc. This paper will document and discuss these default values and their sources for forced air systems.

C.P. Wray, I.G. Theaker, and P. Moffatt. "Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High-Rise Residential Buildings", *Sheltair Scientific Report to the Canada Mortgage and Housing Corporation*, 1998.

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## ABSTRACT

Forced air distribution systems can have a significant impact on the energy consumed in residences. It is common practice in U.S. residential buildings to place such duct systems outside the conditioned space. This results in the loss of energy by leakage and conduction to the surroundings. In order to estimate the magnitudes of these losses, 24 houses in the Sacramento, California, area were tested before and after duct retrofitting. The systems in these houses included conventional air conditioning, gas furnaces, electric furnaces and heat pumps. The retrofits consisted of sealing and insulating the duct systems.

The field testing consisted of the following measurements: leakage of the house envelopes and their ductwork, flow through individual registers, duct air temperatures, ambient temperatures, surface areas of ducts, and HVAC equipment energy consumption. These data were used to calculate distribution system delivery efficiency as well as the overall efficiency of the distribution system including all interactions with building load and HVAC equipment. Analysis of the test results indicate an average increase in delivery efficiency from 64% to 76% and a corresponding average decrease in HVAC energy use of 18%. This paper summarizes the pre- and post-retrofit efficiency measurements to evaluate the retrofit effectiveness, and includes cost estimates for the duct retrofits. The impacts of leak sealing and insulating will be examined separately.

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# ABSTRACT

Energy losses from forced air distribution systems have a significant impact on the energy efficiency of buildings. Little work has been done to quantify these losses in apartment buildings. In this paper we will discuss field measurements made on four forced air heating systems to evaluate the duct system energy losses to unconditioned basements. The apartments were heated by natural gas furnaces located in the basements. The systems had bare sheet metal ductwork exposed to the basement conditions. The pre-retrofit measurements were made on the systems after sealing large easily visible leaks. The post-retrofit measurements were made after wrapping the ducts in foil backed glass fiber insulation and additional leak sealing. Only the sections of duct exposed to the basement were retrofitted because only these sections were accessible. This study examines the potential energy savings for this type of limited retrofit.

The energy losses were separated into leakage and conduction terms. Leakage measurements were made using register flowhood techniques. Conduction losses were estimated by measuring temperatures in the plenums and at the registers. Analysis of the measurements has shown typical reduction in leakage flow due to duct sealing of about 40%. The reduction in leakage translated into a reduction in energy consumption of about 10%.

**Walker, I.S., Wilson, D.J., Forest, T.W. (1996) "A Wind Shadow Model for Air Infiltration Sheltering by Upwind Obstacles", *ASHRAE HVAC&R Research Journal*, **2**(4): 265-283.**

## ABSTRACT

The wind shadow model has been developed to calculate the wind sheltering effects of upwind obstacles for air infiltration calculations. This effect must be determined for infiltration calculations because, in almost all situations, only the unobstructed mean wind speed is known for a building site. This model has adapted the theoretical calculation procedures developed for far wake centreline velocity deficit calculations to near field flows, where shelter has a significant effect. The model uses the concept of a wind shadow projected downstream by upwind buildings to determine the effect of wake velocity reduction on building surfaces. The turbulent nature of the wake is accounted for by "flapping" the wake over a range of wind directions. The effectiveness of this model in accounting for sheltering effects in infiltration calculations has been examined by comparing infiltration model predictions including the wind shadow model to measured data from a row of test houses. The measured data covered a wide range of wind speeds, wind directions and leakage distributions by using over five thousand hours of infiltration measurements from five houses.

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**Walker, I.S., Forest, T.W., (1995) "Field Measurements of Ventilation Rates in Attics", *Building and Environment*, **30**(3): 333-347.**

#### **ABSTRACT**

Field tests were carried out in two flat ceiling, residential attics at a dedicated test site over a two year period. The scope of this paper is to present measurements of ventilation rates, indoor-attic exchange rates, temperatures and wood moisture contents at various locations in the attics. Attic ventilation rates are correlated with wind speed, wind direction, and attic-outdoor temperature difference. Wind speed is shown to be the dominant driving force for ventilation; however, wind direction is important particularly when the attic is sheltered.

**Walker, I.S., Forest, T.W., Wilson, D.J. (1995) "A Simple Calculation Method for Attic Ventilation Rates". In: *Proceeding of the 16<sup>th</sup> AIVC Conference*, Vol. 1, pp. 221-232, Air Infiltration and Ventilation Centre, Coventry, Great Britain. LBL-36879**

#### **SYNOPSIS**

The ventilation of an attic is critical in estimating heating and cooling loads for buildings because the air temperature in the attic is highly sensitive to ventilation rate. In addition, attic ventilation is an important parameter for determining moisture accumulation in attic spaces that can lead to structural damage and reduced insulation effectiveness. Historically, attic venting has been a common method for controlling attic temperature and moisture, but there have been no calculation techniques available to determine attic ventilation rates. Current practice is to use rules of thumb for estimating attic vent areas.

Simple algebraic relationships are developed here, using functions fitted to an exact numerical solution for air flow through attic envelopes. This algebraic model (AVENT) was developed to be easy to use as diagnostic or design tool. Key factors included in the model are: climate (wind and stack effect), wind shelter, leakage distribution and total attic leakage.

This paper validates the model predictions by comparing to measured data from two attics at the Alberta Home Heating Research Facility (AHHRF). Average errors for the model are about 15% compared to the measured ventilation rates.

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